AGARDograph 63

Radio Navigation Systems

FOR AVIATION AND MARITIME USE

A Comparative Study

Technical Editor

W. BAUSS

Pergamon Press

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Radio Navigation Systems

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A Comparative Study

Technical Editor: W. BAUSS

This volume presents a study of an examination and comparison of present long and medium-range navigation systems, applying uniform rules of evaluation. It analyses the extent to which the systems are suitable for common use by civil aviation and merchant marine.

To carry out this task, it was necessary to base the comparative examination of the various radio navigation systems on a common basis, which in consequence forms an essential part of this paper. In the first place, general data is given which indicates the characteristics of the navigation systems and which also broadly outlines their physical bases. Information on the expenditure, in the widest sense of the term as caused by the systems, is presented in tables to facilitate comparison. A special section is devoted to the defining and ascertaining of accuracy and range.

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A Comparative Study

Technical Editor

W. BAUSS

Joint report by the expert committees " Ortung " of the Nachrichtentechnische Gesellschaft (NTG), Frankfurt/M, and " Navigationsverfahren und -Technik " of the Ausschuss für Funkortung (AFO), Düsseldorf, January 1959. Revised in the beginning of 1961

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PREFACE

THE Expert Committee 18 " Location " of the Nachrichtentechnische Gesellschaft within the Verband Deutscher Elektrotechniker and the Expert Committee 4 " Method and Techniques of Navigation " of the Scientific Advisory Committee of the Ausschuss für Funkortung formed a joint committee for the purpose of examining and comparing the present long and medium-range navigation systems, applying uniform rules of evaluation. It was intended to analyse the extent to which the systems are suitable for common use by civil aviation and merchant marine.

To complete this task, it became apparent that it was necessary to base such a comparative examination of the various radio navigation systems on a common basis, which, hence, forms an essential part of this paper. Based upon these descriptions, several tables were compiled presenting a survey of the problems treated. In the first place, general data is given which indicates the characteristics of the navigation systems and which also roughly outlines their physical bases. Furthermore, special questions that may arise with regard to the practical application of the navigation systems are answered in a table for all systems examined. Information on the expenditure, in the widest sense of the term as caused by the systems, are presented also in tables in order to facilitate comparison. Only approximate values are given. This seems to be desirable, for if the absolute values of the prices should change, the relationship of costs remains more or less the same. A special section is devoted to the definition and ascertaining of accuracy and range.

The results of the joint undertaking are laid down in this report. The committee hopes to have made a useful contribution to the discussion of radio navigation systems.

The publication of the translation of this study in the AGARDograph series of AGARD was recommended by the AGARD Avionics Panel, to make this valuable material more widely available to interested scientists and engineers of all the NATO nations.

1. INTRODUCTION

H. C. Freiesleben

NAVIGATION AND LOCATION

Since World War II a large number of radio navigation systems have been available as navigation aids for shipping and aviation. These aids originally were developed for military purposes, but they have since been further developed for use in non-military applications. There is no doubt that the systems are such that they are to some extent not necessary side by side. They all may offer certain advantages so that any one of them would seem to be particularly useful to an individual user; at international discussions they frequently compete for world-wide recognition and introduction.

Radio navigation systems have, in the entire frame of navigation, their own special position, which for the study in hand should be carefully examined in order to clarify the nature of the considerations and the limitations of the devices.

The basic purpose of navigation is to conduct a craft quickly and safely from one place to another. Initially, the route to be followed, the courses and the respective distances (or alternatively the time required for travelling these distances at a certain speed) are determined. Later, *en route* checks are required to check whether and where the craft is travelling on the desired course. Thus a position location will have to be established.

Navigation, therefore, includes dead reckoning navigation with its aids for determining course and speed. In this connection, both the inertial navigation system, which, using only airborne (and shipborne) instruments, by means of acceleration measurements determines the speed and position, and the Doppler navigation system may also be regarded as dead reckoning systems.* Furthermore, position fixing by reference to land targets (terrestrial navigation), sounding and radar navigation is of importance especially for marine navigation.

Position fixing independent of shore-based targets and visibility is rendered possible by the methods of radiolocation. This paper refers to all those methods of radio navigation where, on board ships or aircraft, certain signals transmitted by shore-based or ground stations are received and processed. Primarily, these systems are used for position fixing, and under certain conditions they may be used directly for following a prescribed track.

Finally, astronomical position fixing holds an always important position amongst navigation systems.

* Doppler navigation is based on the oblique radiation of short electromagnetic waves directed to the ground below and a comparison of the emitted and reflected frequencies. The observed frequency difference enables the drift and ground speed of a vehicle to be determined.

In aviation, navigation by dead reckoning may become increasingly important in the future through the continued development of inertial and Doppler navigation, and of automatic dead reckoning equipment. At present, these devices with the accuracy obtainable from them are considered for use in areas not covered by radio aids to navigation or at times when the latter cannot be used for some reason or another.

This may have an effect on the evaluation of radio navigation systems in future. Also the continued development of the astronomical navigation—for example, by the introduction of automatic observation devices and computers, radio sextants, etc.—may influence the evaluation.

RADIO NAVIGATION SYSTEMS WHICH HAVE BEEN EXAMINED

The number of systems to be examined was, to some extent, limited by the terms of reference.

Direction-finding from ground or shore-based stations is not included, since such stations do not transmit signals that can be heard on board ship or aircraft. Bearings taken by ground direction-finding stations as used in aviation are primarily of importance for air traffic control, but not for navigation purposes. When, therefore, shore-based direction-finding is omitted from this report, its importance for navigation under certain conditions should by no means be underestimated—for example, in emergencies, or for craft not provided with radio navigation equipment, or as visual automatic direction-finding of telecommunication emissions for navigational purposes and for facilitating the identification of aircraft on a radar screen.

Radar is also not included in this report.

For *ground or shore-based radar* similar considerations apply as for methods of shore-based direction-finding. No radio signals from such stations are observed and evaluated on board, for this task is performed on the ground or shore, and the result is transmitted to the craft. The exclusion from this report of ground or shore-based radar and of shore-based direction-finding does not imply a judgement of the value of the respective systems.

Airborne radar sets, which are also excluded from this report, are of no vital importance for airborne navigation; they are primarily used for weather observation. In marine services, the importance of *shipborne radar* is restricted to the determination of position in the vicinity of the coast. An estimation of its value as an anti-collision aid, however, is beyond the scope of this paper, which deals with navigation systems only.

Doppler navigation, which has recently come into use for aircraft, is also not included in this report, for Doppler navigation is essentially not a method of position fixing, but an aid to dead reckoning.

A number of systems, by their very nature, are more like the systems to be compared in this paper rather than the navigation aids mentioned above. Such systems are, for example, *Lorac**, *Rana**, *Raydist**, *Shoran**, *EPI**, *High-Fix**. They are not, however, used primarily for navigational purposes, but for surveying work. To include them in this paper would

* See Bibliography, pages 14–15.

thus be of academic interest only and would impair the clarity of comparative presentation.

Similar considerations resulted in excluding such systems which are still used occasionally, as for example, *Gee**, *Rebecca–Eureka** and others, the general introduction of which, however, is not considered.

On the basis of all these considerations, the following systems are examined in this paper:

Direction-finding systems fitted on the ship or aircraft.

CONSOL, Navaglobe, VOR.

TACAN, VORTAC, Navarho.

Decca, DECTRA, DELRAC, Omega, Standard–Loran.

LORAN–C (Cytac), Radio-Mailles (Radio-Web or Radio-Mesh) and the numerous variants of Navarho which use hyperbolic navigation systems.

BASIS OF COMPARISON OF THE SYSTEMS

All these systems are similar in that they provide lines of position. These lines of position are curves on the surface of the earth where a geometrical magnitude, which can be measured on board by means of the system and which is indicated by a visual or aural display as a geometrical magnitude whose *radio coordinate* (e.g. an angle) remains constant. The radio coordinates can only be utilized for navigational purposes if they can be related to geographical coordinates, and this is normally done by plotting on the chart. The lines of position thus established—the methods of entering the radio coordinates in the chart, as applied in practice, vary with the system and application—may differ, to some extent, with the various systems.

The first four systems determine only radial lines of position, i.e. lines which are obtained by observation of the magnitude of an angle. In terms of geometry, the curves on the globe obtained from the craft's own direction-finding equipment are azimuth values and thus they are different from those obtained by the other three systems, where the lines of position are great circles. This difference is not important in practice as long as the area being covered can be regarded as a plane surface. TACAN, VORTAC and Navarho belong to the " rho–theta " systems. This term means that besides an angle " theta " also the range " rho " is determined. The lines of position obtained from these polar coordinates are great circles and small circles.

The last group comprise hyperbolic navigation systems. In hyperbolic navigation, the difference in distance from two transmitting stations is observed. On a plane, the locus of equal distance difference from two points (where the transmitting stations are located) is a hyperbola. This is not strictly correct for the sphere or, still more precisely, for the geoid. Nevertheless, the curve is commonly known as a hyperbola.

Bearing and distance values can be used for plotting the line of position with the usual drawing instruments (course plotter, compass and ruler), provided that charts sufficiently orthomorphic and correct to scale are used. The curves representing the lines of position in hyperbolic navigation

* See Bibliography, pages 14–15

systems are of such a complicated nature that the user cannot be expected to construct them on a chart. Charts with imprinted hyperbolae or similar measures make this superfluous.

A larger section of this paper is devoted to descriptions of these systems, based on uniform points of view. It is difficult to compare objectively such a number of different systems, which originally were intended for different conditions of application, as are now in use in radio navigation. Thus, for example the application of systems in aviation where the space for equipment is restricted, the time available for calculation is short, and the operation of the navigational equipment is by personnel already heavily loaded, calls for extensive simplification of controls and the display of the positional data; and this, in turn, influences design and construction of the equipment. This does not alter the fact that many factors which are important for an evaluation of the system have nothing to do with these peculiarities. This is due to the common task, the position fixing on the earth. The range and accuracy obtainable are characteristic for each system, the wavelength used being of decisive importance because of the frequency-dependent propagation characteristics.

For the whole field of radio engineering only a limited range of frequencies is available, the usefulness of which depends upon the intended application. The continued development and continuously increasing application of radio communications results in a continuously growing scarcity of available frequencies. Therefore, all possible efforts will have to be made to solve a particular problem with a narrow frequency band that is utilized exclusively for the particular application. Hence, *frequency economy* (cf., for example *Radio Spectrum Conservation*, Joint Technical Advisory Committee IRE–ATMA, 1952, McGraw-Hill) becomes an important problem, and the joint efforts of marine and air navigation to find a common system becomes understandable. Therefore, the band width required by the systems examined is also taken into account.

When comparing the *expenditure for the ground equipment*, it must be borne in mind that, for example hyperbolic navigation systems require two transmitting stations for obtaining a family of position lines, whilst in other systems one station is sufficient. As a useful basis for comparison, the expenditure required for establishing a line of position and a position is utilized. Besides the number of stations required, other factors should also be considered, e.g. differences in coverage, etc. Thus, numerical values are possible only to a certain extent. Nevertheless, an attempt has been made to compile a table of certain general data so as to facilitate for the reader a comparison of the economic aspects.

VIEWPOINTS FOR COMPARATIVE CONSIDERATION IN SHIPPING AND AVIATION

This reservation regarding the comparative consideration is particularly applicable when essential characteristics of the various systems are compared in a table. Such a table, if used correctly, will be an important aid for comparative consideration of the various systems. When details are concerned, however, it is necessary to refer to the description of the system in order to do justice to the individual characteristics of the system and to its application.

The requirements of marine and air navigation are essentially different. In shipping, one generally works with nautical charts. The desired routes, free from obstacles, are generally not available, at least not in the vicinity of the coast; the track and the intended course will have to be checked continuously by using chart data or plotting, which requires a continuous knowledge of the geographical position of the ship. Radio position lines are shown on the charts. At sea, of course, fast and simple utilization is also desirable, however; for example, the CONSOL system should not be judged according to whether or not a chart overprinted with CONSOL radials is available, since a CONSOL line of position can be constructed on the chart from other data in a simple manner. In this connection the time required for plotting is of minor importance in assessing the value of systems for marine navigation, although the time factor is becoming increasingly important.

An example of the requirements of position fixing at *sea* is given by the rules established in 1946 by the International Meeting on Radio Aids to Marine Navigation (IMRAMN), which contain the following ranges of navigation and requirements:

Range	*Function*	*Distance to Nearest Source of Danger*	*Accuracy Required*	*Time Available for Establishing Position*
Long	Transocean navigation	More than 50 n.m.	± 1%	15 min
Medium	Aid to approaching land, to coasting and general port approach	50–3 n.m.	± $\frac{1}{2}$ n.m. up to 200 meters	5–$\frac{1}{2}$ min
Short	Aid to harbours and entrance	Less than 3 n.m.	± 50 meters	Immediately

These requirements will certainly have to be reviewed before a decision can be taken at another international conference on the safety at sea. This is also evident from a paper of the Radio Technical Commission for Marine Service (RTCM), Washington, which was written in July 1957 under the title "Application of Electronics to the Marine Services" (SC–30).

However, the IMRAMN requirements roughly define the basic attitude of shipping quarters towards radio aids to navigation.

An example of the requirements of *aviation* with regard to determination of position is given by the recommendations on long-range navigation established in 1957 by the International Civil Aviation Organisation (ICAO–Document 7625) (extract).*

* See also KARWATH, K.E.: *Die Forderungen der zivilen Luftfahrt an ein Langstrecken-Funknavigationsverfahren.* Ausschuss für Funkortung, Düsseldorf. Papers and discussions of the conference held in Essen on Feb. 28th–29th, 1956, Part II, Order No. 2022.

Irrespective of time or weather, a range of the order of 1500 n.m. is desirable. The accuracy must be such that the position-fixing error will not exceed 10 n.m. on at least 95 per cent of the occasions.

The system must have a reliability factor of the highest order practicable. The minimum figure would be 95 per cent of the occasions throughout a flight of 10 hr. The system must contain provisions for an indication in airborne and ground components as appropriate to give warning of malfunctions.

The navigational information displayed by the system must be free from ambiguities that are operationally significant.

The system must be capable of accommodating an unlimited number of users.

The system should be applicable for both air and marine navigation.

The system must provide to the pilot continuous visual indications of the aircraft's position in a manner which will enable him without further processing to follow the designated or required track and make such position reports as may be required.

The desirable requirements are:

(*a*) The airborne portion of the system should be capable of integration with the short-range navigational aid system with the minimum additional devices for computation and visual presentation.

(*b*) A convenient and rapid determination of ground speed.

(*c*) A continuous and quantitative indication of deviation from track; an indication of bearing and distance to or from a selected point within the area of coverage; automatic control of flight; automatic position reporting.

The requirements of aviation concerning medium- and short-range navigation are laid down as general characteristics within the framework of the rules for aids to navigation set up by the ICAO in Part I of the Final Report, Doc. 2553 of the Special Radio Technical Division of the PICAO of 1947, Section 4, " General Functional Requirements for Radio Aids to Navigation ".

Section 6 of this ICAO document contains the basic requirements that have to be met especially by a short-range navigation system, taking into consideration also the specific requirements that should be satisfied by ground stations.

Only very few figures are laid down and are contained in the report of the Special Radio Technical Division of the PICAO of 1947, Doc. 2553, Section 6, Part I, on " Short-distance Aids to Air Navigation ". These figures have not yet been critically examined by the Special Radio Technical Division or by the Telecommunication Division.

In particular there are no details and accuracy data for the individual systems concerning range and coverage, accuracy, ambiguity, reliability, simplicity, operational reliability, safety of interference, site requirements and costs.*

* See also FEYER, W.: *Forderungen der zivilen Luftfahrt an die Mittel und Kurzstrecken Navigation unter besonderer Berücksichtigung der Bodenseite*, Ausschuss für Funkortung, Düsseldorf. Papers and discussions of the conference held in Essen on Feb. 28th–29th, 1956, Part II, Order No. 2022.

The requirements of air navigation and marine navigation with regard to radiolocation are different because of:

1. The particular operational characteristics of an aircraft.
2. The intimate relationship of navigational tasks with tasks of Air Traffic Control service which has to maintain a safe and fast flow of air traffic; the term " safe " in this context includes also " safe from collision ".

Re. 1*:*

(*a*) While the rate of travel of all land vehicles and also of water craft can be controlled nearly from zero to the maximum value without any practical loss of controllability, the speed of an airborne fixed-wing aeroplane, which is considered primarily in this paper, can be controlled to a limited extent only.

The ability and compulsion of aircraft to operate also in the third dimension—altitude—after take-off and before landing—that is to say, when the aircraft is airborne—is subject to technical and economical limitations. Especially the final approach, that is to say that phase of the flight which is the transitional phase from three-dimensional movement during flight into two-dimensional movement after touchdown, also presents the problem of vertical navigation. Considering the distribution of the degrees of freedom of a flight with respect to space and time, results in the following picture:

Prior to take-off, there is full freedom with respect to time; the aircraft may be kept at zero speed; during taxiing, there is a two-dimensional freedom of movement. At the instant when the take-off run begins, the freedom with respect to time becomes zero, and the freedom with respect to space—the take-off run must start at a certain point and must be performed in a designated direction—at first also remains zero. With increasing altitude, the aircraft quickly gains all degrees of freedom with respect to space (which is subject, of course, to the characteristics of the aircraft and any altitude restrictions imposed by Air Traffic Control); it may navigate freely and can utilize its full capacity, which give the aircraft a limited degree of freedom with respect to time during horizontal flight. An aircraft cannot, however, " wait " without occupying airspace. When approaching the airport, the aircraft's degrees of freedom are reduced rapidly. As seen from the target, all movements converge into one point situated on the plane of the airport, the touch-down point, which can be reached in the direction of the extended axis of the runway. During final approach, which is flown along the extended axis of the runway for a distance of 15–20 km, the height above ground and the speed being functions of the distance to the touchdown point, all degrees of freedom with respect to space and time practically remain zero till the end of the landing run, and then they become the degrees of freedom prevailing prior to take-off, that is to say those of a landcraft.

(*b*) In this paper, only systems suitable for *en route* navigation are compared; navigation systems suitable for the take-off and/or final approach phase are not included. However, the following considerations should be borne in mind, which in any case refer to medium-range systems rather than to long-range systems: the navigation systems should render possible in

the most simple manner the transition from the take-off phase into climb and horizontal flight, and also from horizontal flight and descent into the landing phase, in which not only the track but also the height above ground as dependent on the distance to the airport and the speed are prescribed within close tolerances.

A radio navigation system should enable the pilot to keep on the prescribed track with sufficient accuracy, if possible, without any additional processing, according to direct visual display. Furthermore, it should, if possible, provide the pilot continuously with an indication of the distance to the destination or any other unambiguously defined point. When these requirements are met by the navigation system, the position of an aircraft is continuously known although not primarily in geographical coordinates. If such a system exists, the navigational problem of reaching a destination quickly and directly on the planned flight path can be regarded as being solved.

Re. 2*:*

Such a navigation system cannot, however, prevent collisions. Collisions are necessarily likely to occur when more than one aircraft is using the same airspace at the same time, a case which always must be assumed in practice.

In order to avoid collisions, paths must be flown which deviate from those which would have been chosen for meeting the " pure " navigational tasks, provided no other aircraft were in the vicinity. This shows the close relationship of tasks of navigation and air traffic control.

Ensuring a safe flight presents extremely difficult problems, which are becoming still more difficult with the increased and more and more differentiated airspeeds of the various users of airspace. Special reference should be made to one basic aspect of the problem. Even if it were possible to provide each aircraft sufficiently far ahead with information on all movements in its plane of motion that might result in a collision, it would still be impossible to establish unambiguous rules of avoiding action for more than two aircraft that are potential collision risks.

Since these difficulties are inherent in the nature of aviation, the decision on the movements permissible within a certain airspace today rests with the Air Traffic Control service operating from the ground. No reference will be made in this paper to flights to VFR (Visual Flight Rules), where the responsibility rests solely with the pilot. For fulfilling its tasks, the Air Traffic Control service will have to know the position of all aircraft under its control as a basis of its movement control functions, Air Traffic Control measures and instructions. And not only the present position of all aircraft will have to be known, but also the anticipated positions, whose establishment requires the present positions to be known continuously. The anticipated position can be inferred unambiguously from the present only when the aircraft move according to a known plan. Therefore Air Traffic Control prescribes the courses and altitudes of aircraft using airways, especially at medium ranges.

The airway system resulted in the development and application of systems of location supplying radial lines of position—direction-indication radio aids to navigation. The latter permits flying along the designated track directly

according to the display of the space-fixed radio coordinates without any additional evaluation. These radio aids may also be coupled directly to the automatic pilot which would relieve the pilot. The questions of the comparative table of short- and medium-range navigation systems are based on the airway system. This is shown by the affirmative answer to these questions for Rho–Theta navigation systems. Since there is a tendency to replace the rigid airway system by a more flexible system of direct routing for aircraft in upper airspace, the picture may change in the future. The problems of air navigation, then, would be similar to those of marine navigation, which in essence is surface navigation (as distinct from route navigation). In a control system designed accordingly, lateral separation would become more important as compared with longitudinal and vertical separation as applied primarily in an airway system. This trend may lead to varied demands on the location system of air navigation. In addition, there is the requirement of the ground services for increased navigational accuracy within the airspace controlled, in order to utilize the airspace more economically; that is to say, to reduce the space required by any one aircraft.

These remarks refer to the trends in the development of Air Traffic Control as can be foreseen at present. It is still not known whether the special tasks of Air Traffic Control as mentioned above will extend the demands on a radio navigation system beyond its primary purpose, or whether this problem should be solved by other means.

Mention should also be made of the fact that Air Traffic Control requires air–ground communication free from delay and which cannot be impaired by atmospheric disturbances. In certain radio navigation systems, the channels used for navigational purposes may also be utilized for communication.

THE ACCURACY OF A SYSTEM

Some basic general remarks should be made with regard to the important problem of range and accuracy of a navigation system. In all navigation systems supplying lines of position, as is well known, a geometrical curve on the globe is determined, on which a craft that has determined certain data must be located. When two such curves are obtained by two observations, their intersection is then the position. The individual line of position, however, is not absolutely correct, since the data determining the line of position are subject to a certain degree of uncertainty. Due to the uncertainty, therefore, the craft will not be located accurately on the line determined as the locus, but left or right of this line. It is now a mathematical problem to state how far the true position can deviate from the line of position or the intersection of two lines of position.

The theory of observational errors is based on a measurement being repeated sufficiently often, which results in divergent values for the same quantity; the average of the different values is then assumed to be the most probable value. The differences of the individual data from the average constitute a measure of the accuracy, and the probable magnitude of the error of the individual measurements can be calculated from the deviations.

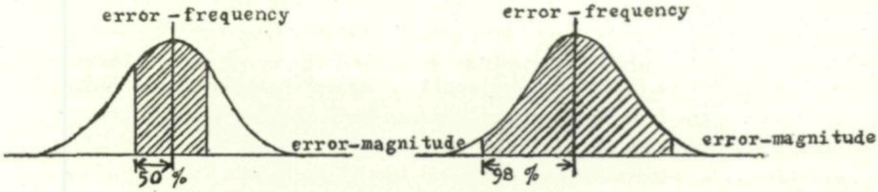
The concept of probability as used in mathematics is not directly applicable in practice. For the user would like to know the maximum

error that he has to take into account. This requirement is expressed in terms of the error theory as follows:

The true position departs from the measured line of position or position respectively by less the p nautical miles with a known probability of, for example, 95 or 98 per cent. There is thus a band of position which is $\pm p$ nautical miles wide for the line of position, and a circular area of radius p for the position within which the craft is considered to be located with a given probability.

Such a statement cannot, however, be made easily. At first, the terms " error " and " probability " will have to be defined, since in measurements made in radio navigation, various sources of errors are involved. Prior to performing probability calculations, such sources of errors should be defined, which either can be used for correction of the measured value, or for disregarding measured data as unusable. Otherwise, bands of position of such a width would be obtained, which would hardly be of any practical value. Errors that are known and that can be allowed for as mentioned above, are known as " *systematic* " or " constant " errors.

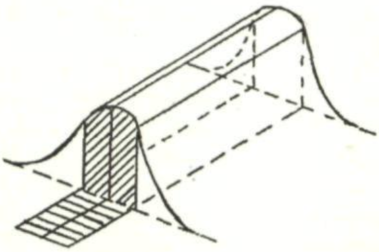
Also, there are the " *accidental* " or " *random* " errors. The Gaussian error-distribution law (gauss error function) is particularly important for this examination. This law says that a certain frequency of values will be obtained when 100 measurements of the same quantity are counted under the conditions of random errors. The great majority of results will be located in proximity to the average, those with greater differences will occur more rarely, and results deviating still more will occur only very rarely. If, then, the number of measurements is plotted against the magnitude of the error, a symmetrical curve will be obtained, since positive and negative differences are equally frequent. At a certain point of the curve, that is to say at a certain magnitude, the probability is 50 per cent. This is that error magnitude which, according to the error theory, determined the width of the band of position within which the craft is considered to be located on 50 per cent of the occasions (probability factor 50 per cent). The much wider band represented by the right-hand figure contains 98 per cent of all errors and thus encompasses all positions that are possible under the given assumption.

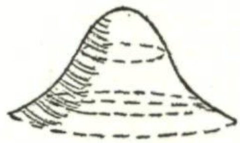


This is the width in which the user is interested, since it ensures him that his position is really within this band on 98 per cent of the occasions.

The error distribution should be visualized as a mountain ridge, whose axis is the line of position and which has also a certain width and height because of the error distribution. If position-fixing is involved, that is to say, the intersection of two lines of position, two intersecting mountain

ranges should be imagined, which then form an oval hill. That plane of the hill intersecting with the chart plane, with the height of the intersecting plane depending on the probability factor, gives an oval area. In further calculations, this area is replaced by a circular area, which encompasses





equally many positions; for example, 95 per cent of all values. The radius of this circle is known as the radius of the circle of error. It indicates to the user the maximum deviation from the true position expressed in kilometers or nautical miles at which he is located with a given probability.

Besides such probability considerations, the effect of the errors on the line of position should be examined for each system. In most radio navigation systems, the effect of an error of the measured value within the area covered by the radio aids to navigation is of different magnitude at different points. If the line of position, for example, is a great circle, the accuracy of the distance to the transmitter is determined by the simple function $\sin d$ ($d =$ distance in radians). In hyperbolic systems or direction-finding systems on board ship or aircraft, these effects of an error in the measured value, which are governed by mathematical laws, are more difficult to determine. In any case, however, the result is that the width of the band of position is determined not only by the spread of the observations, but also by the location of the position relative to the ground station of the radio aid to navigation. For practical purposes, of course, only the combined effects of these geometrical relationships and the probability considerations are of interest.

The error theory is based on the occurrence of random or accidental errors, which may occur, for instance, when reading an instrument. Only errors of this type fall within the Gaussian distribution mentioned. When the sources of an error are of a physical nature, the error frequency may be of an entirely different type. These errors are known as systematic or constant errors. Such systematic errors may occur owing to peculiarities of propagation of electromagnetic waves. Theoretical and experimental investigations in this field showed only in a few cases a possibility for taking into account such errors. In other cases, random errors occur temporarily as a result of physical conditions; however, such errors will change relatively quickly and over a longer period of time they are of a statistical nature. The latter cases may be also treated in principle according to the laws of probability. A system may be unsuitable because of the magnitude of errors determined by physical factors; for then the band of position of a 98 per cent probability becomes so wide that no practically useful information

can be obtained. Therefore, this system will not be used. The night effect on a direction-finding system installed in a ship or aircraft, for instance, is so great that this system can be applied only during daytime; in other methods, allowance can be made for the night effect by using a probability factor greater than during daytime. Thus, the accuracy is not evaluated schematically but by taking into consideration individual conditions, which vary with the method applied.

The question whether errors of observation are correlated is not easily susceptible to systematic treatment; it is also a problem relating to the physical aspect of errors which is not easy to understand. Two magnitudes are said to be correlated if there is a systematic relationship between them, that is to say, when the change in one magnitude is accompanied by a change in the other magnitude. Such a correlation of two data is not to be expected for the radial lines of position as obtained from Rho–Theta systems. In the case of Rho–Theta systems such correlation would change only the error distribution but not the size of the circle of uncertainty. But it may be assumed that in hyperbolic systems where one Master station controls several Slave stations, a large error exists in all families of hyperbolae if there are certain fluctuations in the transmission path from the Master station, because such fluctuations would also affect the Slave stations in most cases. Correlations occur due to some physical reasons where each individual type of error may be composed of random errors. Examinations of the occurrence of correlations are cumbersome and require long statistical series. The mathematical evaluation of such correlations modifies the typical Gaussian error distribution.

So the examination of range and accuracy is generally based on several conditions. The necessary attempt to arrive at a comparative evaluation, which is based on individual data, is only a limited success. For when considering the value of such individual data for the evaluation of the systems, their limitations should be borne in mind. It should be also remembered that this paper refers only to the accuracy of the systems with regard to position fixing, and not to the track guidance accuracy of sea or aircraft.

CONCLUDING REMARKS

The Committee (see page v) did not indicate quality factors although the Commission spent a long time in establishing them. The attempt was rather to collect the most important figures together in order finally to obtain one single value for each system and thus create an order of precedence. This idea cannot, however, be translated into practice, for the individual figures can be related to each other in one equation only by arbitrary simplification. The viewpoints are too diverse for significant conclusions to be reached in this way.

This paper is based on the stage of technological development at the date when the examination was concluded. The possibility of further development of many other equipments and methods may be assumed. However, the members of the Committee of this report could not undertake to make anticipatory statements and thus to run ahead of reality. Nevertheless, an attempt has been made in this paper to establish general principles

for comparative examination of future developments as well. Therefore, in many instances the wording was chosen rather carefully.

This paper will not relieve the reader of the decision he has to make with regard to the radio location and navigation systems suitable for a particular application. It is intended, however, to assist him by presenting the greatest possible number of viewpoints and by attempting to present to him objectively all possible aspects.

SUPPLEMENTARY REMARKS ON "INTRODUCTION"

It was only after the manuscript of this " Comparative Study " was completed that additional operational inaccuracies became known of the VOR/DME and Decca systems. Such information was presented by the U.S. and U.K. delegations to the " Special COM/OPS/RAC Meeting of ICAO " in Montreal, in February 1959 (Short-Distance Navaids). It should be mentioned, therefore, that only the manufacturers data, and data from other sources, concerning in particular accuracy and range were available for this report.

The great many documents of the Montreal conference contain new data on errors as obtained from experience, with these errors resulting from the accuracy of the airborne equipment, and on pilotage or flight technical errors respectively resulting from the transmission of the instrument readings to the aircraft controls. Both types of error are, of course, different for the different systems, and exercise a different influence on the overall operational accuracy, depending on the system involved (hyperbolic or rho–theta system).

With regard to errors due to the inaccuracies of shipborne equipment, reference should be made to several Court of Admiralty rulings which state it to be an offence or at least negligence if the Master relies on one navigational aid only; such errors should be avoided as far as possible by using different kinds of Navaids. The equivalent of flight technical errors does not occur in marine navigation since there is no transmission of navigational data to the ship's rudder.

Flight technical errors are of considerable importance. It should be borne in mind that radio navigation systems for civil aviation not only serve navigational purposes but also form the basis for the horizontal separation of aircraft flying under Instrument Flight Rules so as to avoid the danger of collision. The separation minima are determined by the navigational accuracy to be expected in the area concerned. This is not equal to the accuracy of a radio navigation system derived from physical considerations and mathematical calculations. The decisive factor is the navigational accuracy to be expected in practice. Inasmuch as flight technical errors may adversely affect safety in the same way as the physical errors of a system, the former should be taken into consideration when a navigation system is assessed.

It proves very difficult to compile statistics on flight technical errors. To measure them correctly would require the continuous recording of the navigational data indicated. At the same time, the actual flight path flown by using such navigational data would have to be checked by optical instruments or radar. Since data on flight technical errors of acceptable

reliability are available only for one or two systems, this factor could not be taken into consideration in order to make sure that the systems descriptions and the tables are comparable. The flight technical error is also not considered in Chapter 5 on " The Accuracy of Radio Navigation Systems ".

A certain idea of the flight technical error to be expected can be derived from information on the nature of the radio coordinates, their map evaluation, their suitability for connection to the automatic pilot, on the operation and handling of such systems and, for instance, information on the resolution of ambiguities. It must be left to the reader to inform himself on the probability of flight technical errors as an important criterion of the suitability of radio navigation systems.

Blunders and gross human errors of the kind dealt with at the conference held by the Royal Geographical Society of London, in June 1958, are also not taken into account (see *J. Inst. Navig.*, Vol. XII, No. 1, January 1959).

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2. DESCRIPTION OF THE SYSTEMS

2.00. INTRODUCTION

In the following chapters sixteen radio navigation systems are described which either have been implemented and serve the navigation of ships or aircraft, or whose implementation can be accomplished due to their standard of technical development. The descriptions follow a certain pattern, outlined below, in order to facilitate comparison and evaluation of the systems by the reader.

PATTERN OF SYSTEM DESCRIPTION

1. *General Introduction*

Brief historical review indicating the purpose for which the system was developed, present technical status, remarks on the development planned for the future.

2. *System Description*

Information on the type of radio coordinates and lines of position.

The system description indicates to which group the system belongs (Rho–Theta, hyperbolic), explanation of the physical principles, justification of the frequency range, problems of propagation.

3. *Accuracy and Range* (*Coverage*)

This section presents information obtained from other publications, with reference to part 3 of this report on " Accuracy and Range (Coverage) " of radio navigation systems.

4. *Navigational and Operational Considerations*

Description based on and explanatory to the information presented in Table 4.2.2.

5. *Ground Installation and Airborne* (*Shipborne*) *Equipment*

As section 4, referring to the information presented in Table 4.3.

2.01. RADIO DIRECTION-FINDING ON BOARD AIRCRAFT AND SHIPS

W. T. Runge

1. GENERAL INTRODUCTION

Radio direction-finding* is one of the oldest methods of radio navigation. Short- and medium-range radio direction-finding has been used in marine navigation since the twenties. The International Agreement on Safety of Life at Sea concluded in London in 1948[11] stipulates that all vessels of a gross tonnage of more than 1600 tons must be equipped with a radio direction-finder. See also Fig. 4.

Coast lines and air traffic areas are equipped only with special ground transmitters known as " radio beacons " (Fig. 4).

In aviation the instrument used for radio direction-finding is the radio compass.

The system has been developed to a high degree of perfection. Only with technological progress will the radio direction-finding equipment be reduced in bulk, and its operation be simplified and become more reliable.

2. SYSTEM DESCRIPTION

The voltage received by a rotatable loop antenna is zero when the plane of the loop antenna is perpendicular to the direction of propagation of the wave received (Fig. 1.1). Since the waves are propagated rather precisely

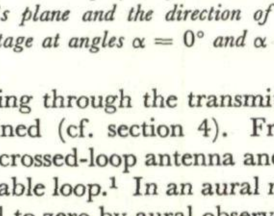

Fig. 1.1. Voltage R_R induced in loop (seen from above) as function of the angle between normal on the loop's plane and the direction of incidence α of the wave. Sharp zeros of induced voltage at angles $\alpha = 0°$ and $\alpha = 180°$.

along the great circle passing through the transmitter location, radial lines of position are thus obtained (cf. section 4). Frequently, an equivalent combination comprising a crossed-loop antenna and a goniometer (Fig. 1.2) is used in place of the rotatable loop.[1] In an aural null direction-finder,[8] the received voltage is adjusted to zero by aural observation and rotation of the

* Note: The term " Radio direction-finding " as used in this paper is defined specifically as " determining the bearing of radio transmitting stations by means of an airborne or shipborne radio direction-finder ".

orientation of the loop antenna. The interfering influences of secondary radiators on the definition of the minimum observed with the aural null direction-finder (Fig. 1.3) are compensated by a voltage derived from an

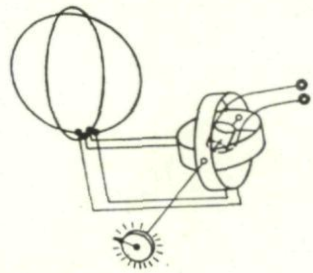

Fig. 1.2. Crossed loops and goniometer.

The voltage induced in the rotatable coil is equivalent to the voltage induced in rotatable loop at same angle of rotation.

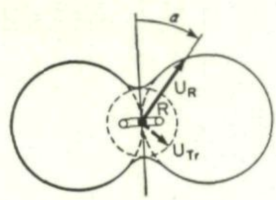

Fig. 1.3. Superposition of voltage induced in ideal loop and omnidirectional error voltage UTR 90° out of phase.

Blurred minima instead of sharp zeros of loop voltage U_R.

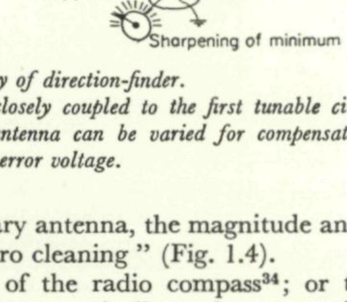

Fig. 1.4. Input circuitry of direction-finder.

A rotatable loop is closely coupled to the first tunable circuit. The coupling of the untuned auxiliary antenna can be varied for compensating the omnidirectional 90° degree out of phase error voltage.

omnidirectional auxiliary antenna, the magnitude and sign of which can be properly adjusted, " zero cleaning " (Fig. 1.4).

The rotatable loop of the radio compass[34]; or the search coil of the goniometer is adjusted automatically to the zero-position by a servo device (Fig. 2.2).

In the Watson-Watt direction-finder the inputs of two identical receivers are connected to the fixed crossed-loop antennas. The receivers supply two high- or intermediate-frequency voltages to a cathode-ray tube producing

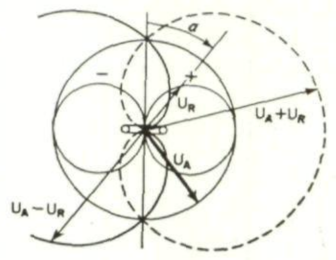

Fig. 2.1. Superposition of loop voltage U_R *and voltage of vertical antenna of equal phase and magnitude.*

Since the voltages corresponding to the two halves of the loop characteristic have opposite phase, the resulting diagram is kidney-shaped (cardioid). The two curves corresponding to the sum $U_A = U_R$ *intersect at angles* $\alpha = 0°$ *and* $\alpha = 180°$.

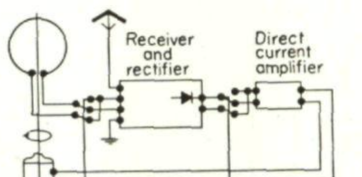

Fig. 2.2. Principle of radio compass.

The sense of rotation of the motor is determined by the position of the switch supplying the stronger signal. The motor turns the loop until the signal has the same amplitude for both positions. Only one of the two corresponding orientations of the loop being stable, the indicated direction is unambiguous.

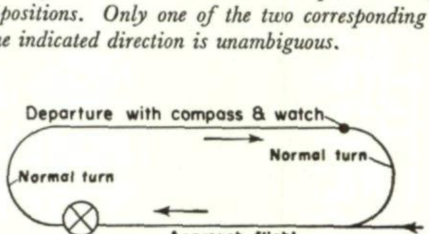

Fig. 2.3. Waiting area in the vicinity of a radio beacon.

there a straight line whose direction corresponds to that of the incident electromagnetic wave (Fig. 3).

When the polarization of the wave incident at the elevation angle *e* deviates by the angle *k* from normal polarization (horizontal magnetic field

strength), the bearing error φ of the radio direction-finder is determined by the following equation: $\tan \varphi = \tan k \sin e$. In the case of the ground wave, e and k are zero. Therefore, the bearing error is also zero. In the case of sky waves, however, the polarization generally is not normal; both e and k differ from zero, the latter value being variable. When sky waves are received, bearings taken with the radio direction-finder, therefore, comprise an unsystematically fluctuating error whose magnitude may be substantial.[13]

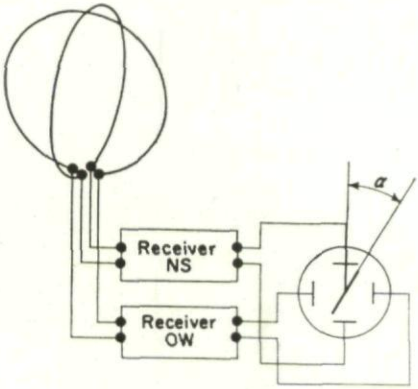

Fig. 3. Watson–Watt's direction-finder.

Two receivers having same amplification and phase shift furnish the received frequency or an intermediate frequency.

The presentation of both voltages on our oscilloscope produces a line, the direction of which corresponds to the direction of the incoming wave.

Bearings can be taken reliably only within the area where the ground wave predominates. During daytime and with frequencies below 300 kc/s, this range extends up to several thousand kilometres over sea water; at night, the range is reduced to approximately 100 km. The range reduces to less than 100 km at day and night with frequency increasing up to 4 Mc/s. With frequencies above approximately 2 Mc/s, reflections from nearby structures impair bearings; no useful bearings can be obtained with frequencies in excess of approximately 4 Mc/s.[6]

Attempts were made to eliminate the error caused by the rotation of the plane of polarization which occurs in the ionosphere, by transmitting pulses with steep leading edges and using only the first portion of the received pulse. This portion is due to the ground wave arriving earlier than the sky wave. However, for direction-finding these methods have not gained ground.

On wide unobstructed surfaces free from interfering reflectors, antenna systems can be constructed which will respond only to the normally polarized component of the radiation received (Adcock direction-finder). Such systems, however, fail on ships and aircraft since they are extremely sensitive to field distortions due to reflectors nearby.

For radio direction-finding no particular bandwidth requirement exists. Bearings can be taken even of unmodulated transmitters with zero bandwidth. Transmitters normally use a bandwidth of $\pm$ 1 kc/s, because identification must be provided either by modulation or by keying.

3. ACCURACY AND RANGE (COVERAGE)

The range (coverage) of radio direction-finding systems is limited not only by the requirement that the ground wave predominates (cf. section 2). It is also limited by the requirement that the field strength of the signal received must be greater than the atmospheric noise level at the receiver site. 50 μV/m are sufficient. This requires the following radiated powers over sea:

f	*100 km*	*2000 km*
kc/s	*W*	*kW*
50	0.3	1.0
100	0.3	2.5
300	0.3	22.0

The deviation from the great circle may be neglected in the case of ground waves over sea water.

The measuring accuracy of the receiver is limited by the equipment noise. The angle within which the signal is drowned by the equipment noise shall be less than $\pm$ 0.5° at a field strength of 50 μV/m. The centre-line of this angular sector can be estimated to approximately 1/10th of the width of the angle. In modern radio direction-finding receivers approximately 15 μV/m are sufficient for a minimum width of 1°. The systematic (quadrantal) bearing errors of up to approximately 20° caused by untuned conducting structures in the vicinity can be calibrated and compensated for. The standard deviation of the equipment bearing error of a compensated radio direction-finding receiver is less than $\pm$ 1°.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

4.1. *Navigational Considerations*

Radio direction-finding techniques supply the direction of the great circle on which the observed transmitter is located. It is, therefore, a suitable method of homing.

In order to determine the position, the true bearing will have to be obtained. North is supplied by the compass with a standard deviation of approximately $\pm$ 1°, therefore the standard deviation of the true bearing is approximately 1.4°. The true bearing can be plotted directly on the chart as a radial line of position through the transmitter when the distance to the transmitter is small. This procedure is permissible if the difference in longitude between transmitter and position is less than 2°, or if transmitter and position are located on different sides of the equator. Otherwise the curve connecting all loci of equal true bearing would depart too much from the great circle on which the transmitter is located. Corrections then will have to be taken from tables.[7]

4.2. *Taking a Bearing*

At first the radio direction-finding receiver must be tuned to the transmitter.

4.2.1. When an aural null direction finder is used,[8,9] a zone of minimum reception is found by rotating the goniometer (Fig. 1.3). Then the zero sharpening control is adjusted so that reception is null in the centre of the minimum zone (Fig. 1.4). This position indicates the bearing relative to the longitudinal axis of the craft. The bearing scale frequently is a slave of the ship's compass. Then the bearing is read relative to magnetic or true north.

The bearing is perpendicular to the plane of the loop antenna. Therefore it is ambiguous. In order to eliminate ambiguity, the " Side Selector Switch " is placed into one of two positions marked by different colours. The colour of the position of minimum reception indicates the correct side on the bearing scale.

Since the minimum is observed aurally, the operator can judge the reliability and accuracy of the bearing taken. When several transmitters whose signals can be distinguished aurally are received simultaneously, a skilled operator can take bearings of both transmitters separately. This requires, of course, increased attention on the part of the operator; the accuracy is reduced.

While bearings are being taken, messages cannot be received simultaneously.

The aural null direction finder owes its popularity and extensive use to the possibility of judging the quality of a bearing directly, and to its simplicity.

4.2.2. The radio compass[3,4] need only be tuned; no further manipulation is required. The loop antenna or the goniometer search coil is rotated automatically into the correct direction without ambiguity (Fig. 2.2). The bearing can be read directly from an instrument in the cockpit. Passing over the transmitter is indicated by a sudden change of the bearing from 0° to 180°; approach and holding procedures use this marked indication (Fig. 2.3).

In aviation the radio compass is preferred because of its simple mode of operation, remote tuning control and remote data display. The operation of more recent types of equipment is even more simple by the use of crystal-controlled channels which can be selected within the frequency band at a 500 c/s spacing and which can be adjusted on a counter. The Model AD712 and AD360 (Marconi) are examples of such equipments. More recent instruments are transistorized.

While bearings are being taken, messages can be received simultaneously without interference.

The radio compass supplies unambiguous bearing information useful for remote display. The quality and reliability of a bearing taken can hardly be judged, for when several transmitters are received at the same time, the radio compass will indicate a bearing which cannot be identified with any one transmitter. It is a condition for the application of the radio

compass that within the receiver bandwidth the frequency channel of the radio beacon on which a bearing is taken is left free of other transmissions. Fluctuating pointer deflections due to thunderstorms cannot be avoided.

4.2.3. The bearing obtained by means of a Watson–Watt direction-finder can also be read directly after tuning the receiver to the transmitter. Since a bearing error will occur when the amplifications of both receivers are unequal, equality of amplification will have to be checked and, if necessary, adjusted prior to taking a bearing. For this purpose both receiver inputs are connected in parallel. The tracer line should then indicate 45°. The angle obtained in taking a bearing is ambiguous. By operating the side selector switch, one half of the tracer line can be obscured.

While bearings are being taken, messages from the transmitter can be received without interference.

The Watson–Watt direction-finder combines direct indication of the bearing with the possibility of judging quality of the bearing by means of the picture on the cathode-ray tube screen. When two transmitters are received in the same channel both bearings are shown on the cathode-ray tube screen. This advantage is obtained at the expense of more costly equipment.

5. GROUND STATIONS AND AIRBORNE (SHIPBORNE) EQUIPMENT

5.1. *The Airborne (Shipborne) Equipment*

5.1.1. On ships, fixed crossed-loops are normally used which are either screened (area 0.7 m^2) or free wire loops (area several m^2).[2]

The receiver is connected to the crossed-loops by means of a two-pair core cable up to 30 m long.

The aural null radio direction-finder is extensively used on ships since it is a very simple piece of equipment comprising the goniometer and a sensitive and selective receiver. Prices, weight and dimensions of commercial equipment are listed in Table 4.3.

5.1.2. Also the Watson–Watt direction-finder is becoming more popular. The equipment comprises two receivers and a cathode-ray tube instead of the goniometer. The tracer line indicates the bearing which can be read from a scale provided around the cathode-ray tube. The bearing indicated either relates to the main axis of the craft or, if the scale is a Slave compass, to magnetic or true north. Prices, weights and dimensions of commercial equipment are listed in Table 4.3.

5.1.3. Recently Marconi developed a marine radio compass " Lodestar ", Model 2464A.[12] Since the stringent requirements of the Treaty on the Safety of Life at Sea[11] and of the regulations of several States based on the former cannot be met fully by the radio compass (see section 4.2.2, p. 24) it can be switched over to manual operation and then be operated as an aural null radio direction-finder. For price, weight and volume, see Table 4.3.

5.1.4. On aircraft, only the radio compass is used, because tuning to the respective transmitters is the only manipulation required. The bearing

can be read unambiguously from the instrument on the instrument panel. The antenna was formerly of the air-core frame type of approximately 20 cm diameter in a little streamlined dome. The next step of development was a ferrite coil system which is incorporated in a covered shallow recess in the skin of the fuselage. The radio compass DFA70 (Bendix) and AD7092D (Marconi) are good examples of this type of equipment. The most recent stage of development is a very flat ferrite crossed-loop with a miniature goniometer. This system avoids the mechanically complicated servo-controlled rotating loop in the fuselage skin. The Models AD712, AD722 and AD360 of Marconi and ADF102 of Lear are examples of this type of design.

5.2. *Ground Stations*

On the ground, radio direction-finding requires only transmitters of sufficient power and suitable frequency (cf. sections 2 and 3). The position of the transmitters must be known and identification must be easy. Since suitable commercial or broadcasting stations are not always situated in suitable locations and are not always radiating when bearings are required, radio beacons are provided in suitable locations. The power of such radio beacons as used in marine navigation is from a few watts to 100W, their frequency band from 285 to 315 kc/s. They are modulated and provide an identification signal. They are erected along the coast, especially also on lightships[7,10] (Fig. 4).

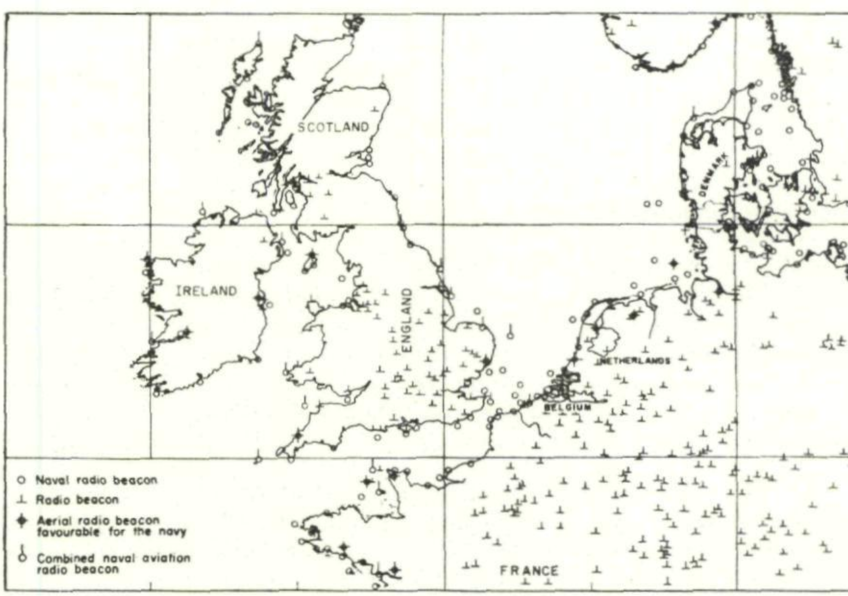

Fig. 4.

In aviation, keyed transmitters are used, operating in the 200–415 kc/s band, their power extending from 100 to 300W in individual cases up to 5 kW.

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2.02. CONSOL AND CONSOLAN

E. Kramar

1. GENERAL INTRODUCTION

" CONSOL ", the international designation of the German radio navigation aid " Sonne ", was developed from the " Elektra " beacon. This *directional radio beacon* was designed in 1940 with the aim of obtaining a long-range navigation system of high accuracy. Only a modest amount of airborne (shipborne) equipment should be required.[1] The position lines were defined by equisignal zones. Accuracy was increased by the use of a multi-lobe pattern produced by combining the fields of two antennas spaced a few wavelengths apart. Thus a radiation pattern (fan) originated consisting of alternate sectors of dot and dash signals separated by equisignals. The orientation of the equisignal could be adjusted by shifting the phase of the antenna currents, with the restriction, however, that only one equisignal could be aimed to the respective target at a time.

The slow *rotating radio beacon* Sonne was developed from this directional beacon in 1942. In the Sonne system the equisignals and sectors rotate continuously and uniformly in space, consecutively replacing the dot sectors by the dash sectors and vice versa. After each cycle the pattern reverts to its original position. Due to the compulsory coupling of the rotation with the keying facility required for producing the dots and dashes, the instantaneous position of the equisignals relative to the initial position of the fan can be determined by counting the characters received until one equisignal line passes the observer.

The transmission sequence is composed of the navigational (keying) cycle (combination of 60 dot and dash characters), a long dash, the identification signal and a short interval (see Fig. 1 and Table 1).[1,7,14]

Since then the CONSOL system has hardly changed.[2,3,14] All suggestions for modification failed because they were not compatible with the original simplicity of the system that is one of its foremost advantages, as the user requires no special receiver and equipment for reception and evaluation.

A CONSOL ground station employs three aerials sited in a straight line (section 2: description of principle). A slightly modified version with only two antennas, but using the same method as CONSOL for keying and for rotating the equisignal fan, was tested in the U.S.A. 1949–50 under the designation " CONSOLAN " (Radio Set AN/FRN–5).[3,4] Some stations operating on this principle are being installed in the U.S.A., one of them at Nantucket has been in operation since the beginning of 1958[13] and in San Francisco, Cal., since 1960. The Nantucket station belongs to the CONSOL plan proposed in 1956 by a technical committee of the ICAO for the coverage of the North Atlantic with stations in Iceland, Greenland, Canada, the U.S.A. and the Azores. Figure 2 gives one of the maps, showing seven new stations in addition to the existing five European

CONSOL stations. The solid line comprises the area in which the fixing accuracy to be expected is equal to or better than 10 n.m. during daytime and better than 20 n.m. during night-time for 95 per cent of observations taken (see explanation of Fig. 2).

Since 1960 two CONSOL stations have been in operation in Russia in the Arctic Sea region (see table).

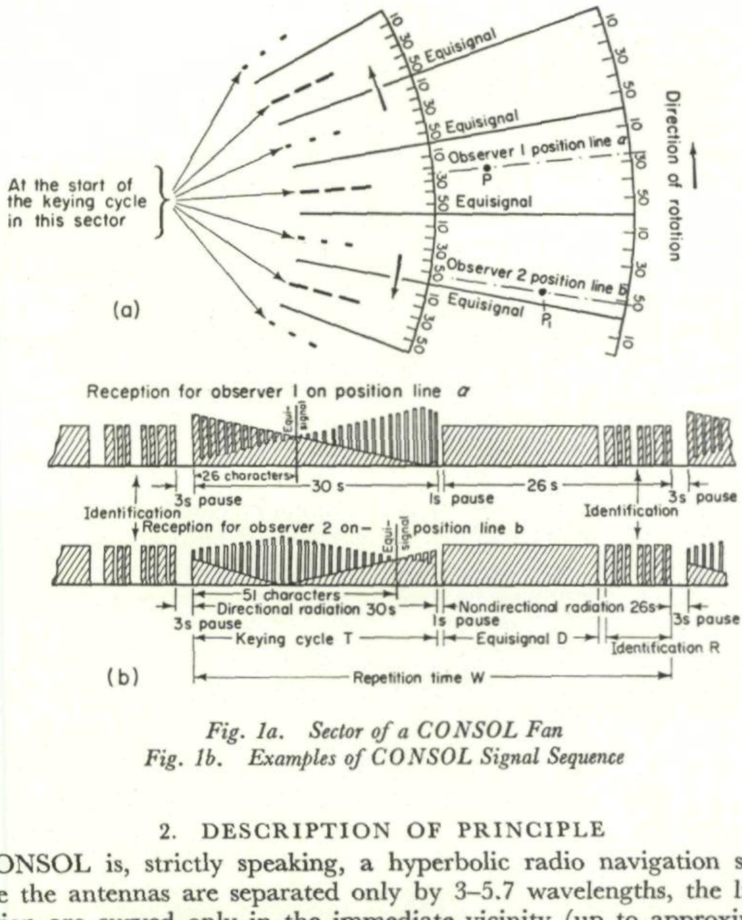

Fig. 1a. Sector of a CONSOL Fan
Fig. 1b. Examples of CONSOL Signal Sequence

2. DESCRIPTION OF PRINCIPLE

CONSOL is, strictly speaking, a hyperbolic radio navigation system. Since the antennas are separated only by 3–5.7 wavelengths, the lines of position are curved only in the immediate vicinity (up to approximately 20 wavelengths distance). At greater ranges they practically coincide with the asymptotes. Therefore, CONSOL is as a rotating radio beacon classified amongst radio navigation systems, which provide radial lines of position.

Because the equal phase lines of a composite radiation pattern are unsuitable for measurements by simple methods, CONSOL employs two alternately shifted patterns produced by a 180° phase keying in a dot-dash rhythm, thus forming the equisignal fan. The slow rotation of the fan is obtained by an additional continuous phase shift of the currents through the two outer antennas.

CONSOL—Stations (in the beginning 1961)

Station	Geographical Station	Frequency	Main Equisignal	(s. Fig. 1b)	Repetition Time and Number of the Bearing per 10 min.
Bushmills (Ireland)	55° 12′ 20″ N 06° 28′ 02″ W	266 kHz	130 13′	T 30 D 4 R 2	W = 40 Z = 15
Ploneis (France)	48° 01′ 06″ .08 N 04° 12′ 54″ .16 W	257 kHz	106° 12′ 286° 12′	T 30 D R 4	W = 40 Z = 15
Stavanger (Norway)	58° 37′ 31″ N 05° 37′ 40″ 0	319 kHz	067° 247°	T 30 D 19 R 4	W = 60 Z = 10
Lugo (Spain)	43° 14′ 53″ .29 N 07° 28′ 53″ .89 W	285 kHz	088° 30′ 268° 30′	T 30 D 18 R 4	W = 60 Z = 10
Sevilla (Spain)	37° 31′ 17″ .44 N 06° 01′ 48″ .06 W	315 kHz	083° 263°	T 30 D 19 R 4	W = 60 Z = 10
Kanin (Russia)	68° 38′ 18″ N 43° 23′ 30″ 0	269 kHz	175.5°	T 30 D 10 R 6	W = 60 Z = 10
Rybacij (UdSSR)	69° 45′ 12″ N 32° 55′ 0″ 0	363 kHz	25°	T 30 D 10 R 6	W = 60 Z = 10
Nantucket, Mass. (U.S.A.) CONSOLAN	41° 15′ 35″ N 70° 09′ 15″ W	194 kHz	025° 205°	T 30 D 0 R 7,5	W = 42.5 Z = 13
San Francisco, Cal. (U.S.A.) CONSOLAN	38° 12′ 12″ N 122° 34′ 19″ W	192 kHz	50° 230°	T 30 D 0 R 7,5	W = 42.5 Z = 13

T = Keying cycle D = Equisignal R = Identification
W = Repetition time Z = Number or bearing per 10 min.

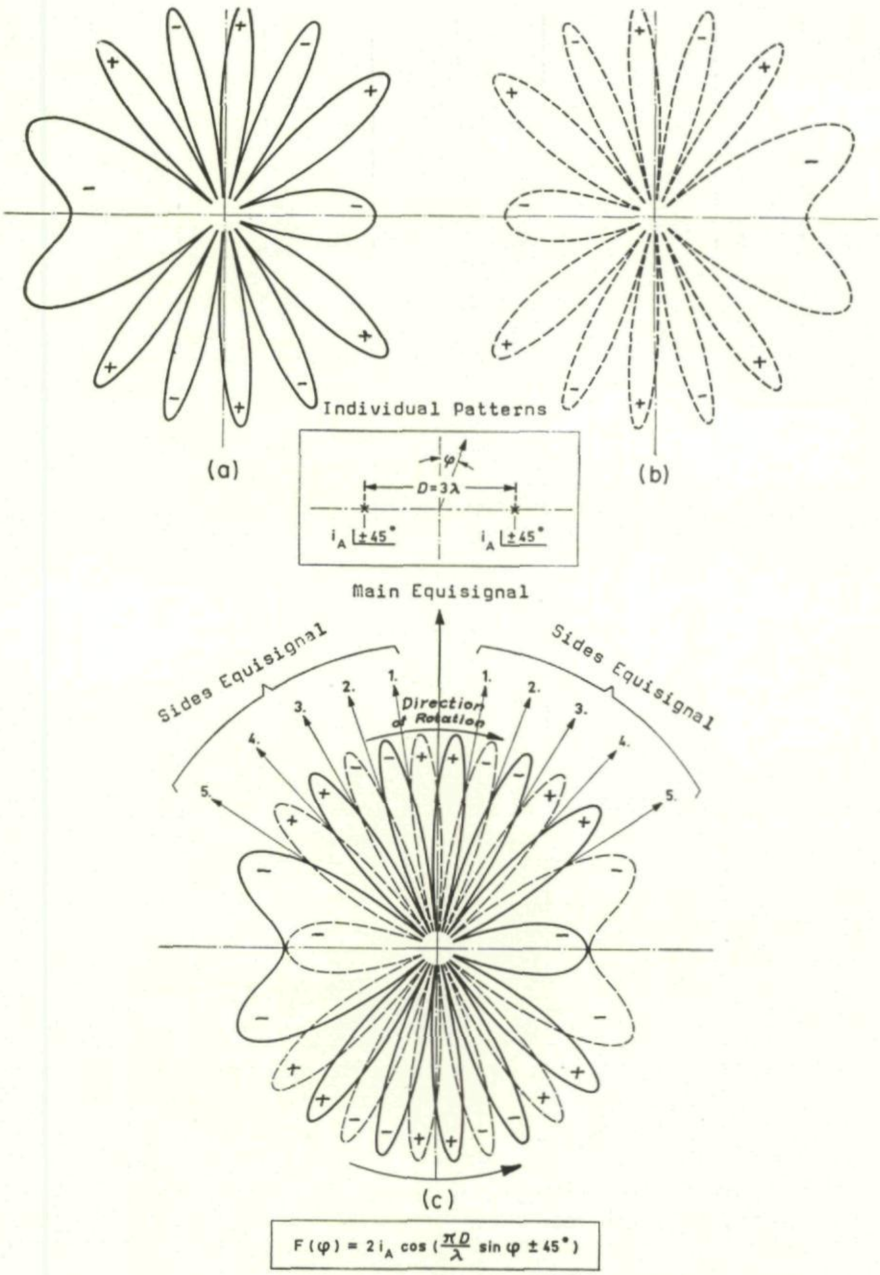

Fig. 3. Azimuth type pattern of a two mast installation, mast spacing $D = 3\lambda$
3a. Phase difference of antenna currents $\varphi = +90°$
3b. Phase difference of antenna currents $\varphi = -90°$
3c. Keying between $\varphi = +90°$ and $\varphi = -90°$ generation of equisignal lines

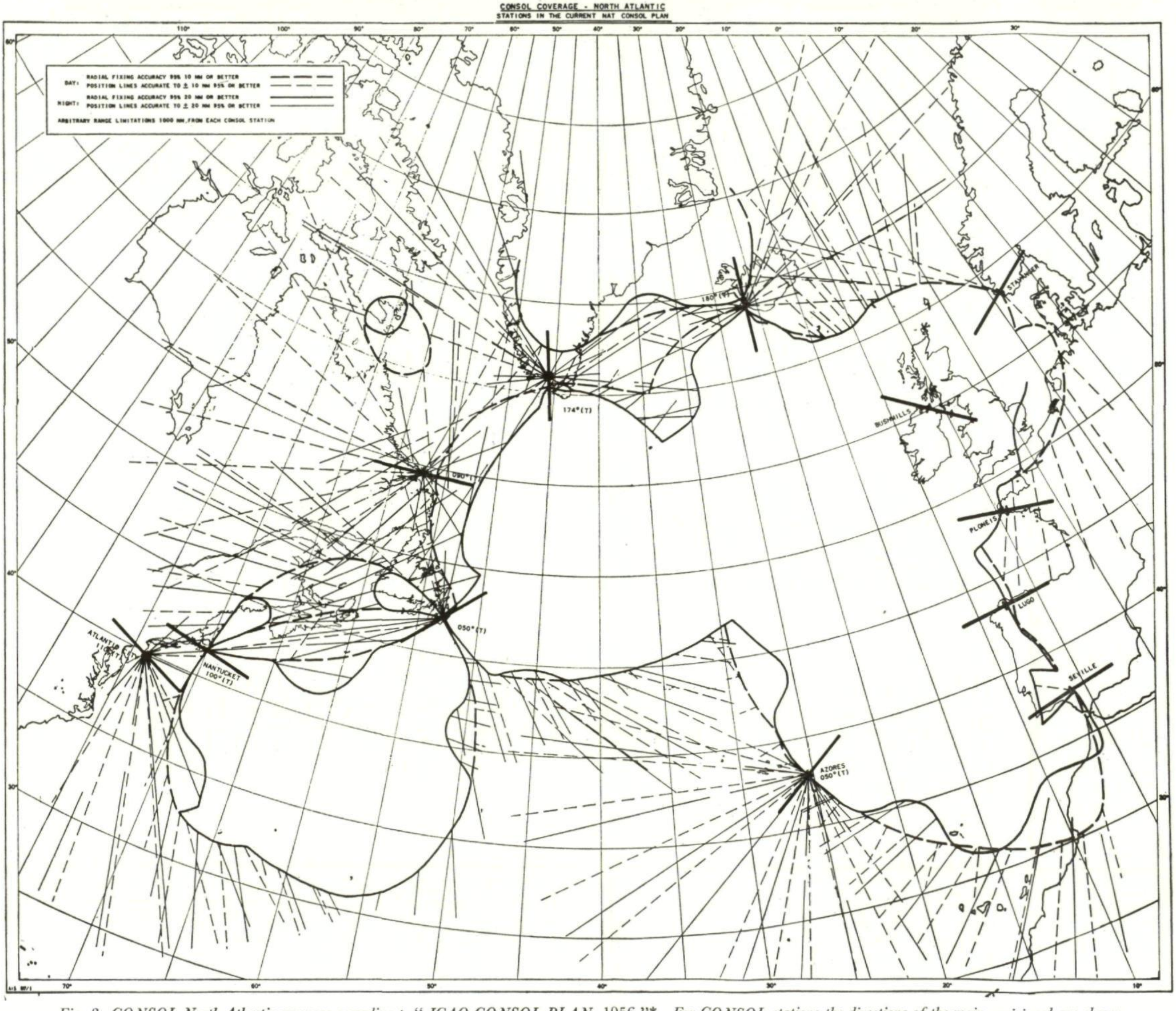

Fig. 2. CONSOL North Atlantic coverage according to "ICAO-CONSOL-PLAN, 1956 *"*. For CONSOL stations the directions of the main equisignal are shown by a bar* (———)

Estimated range of :x 1000 *n.m.*v

Deviations (95% *probability*) *:*

daytime :x 10 *n.m. within area* — — —

position line 10 *n.m. within area* — — —

night time :x 20 *n.m. within area* ———

position line 20 *n.m. within area* ———

* *The main equisignal of the Nantucket installation was adjusted* 25° *which deviates from the initial planning.*

To face page 30

In principle only two radiators are required with a spacing of a few wavelengths and fed by the same carrier (Fig. 3).

The phase-keying necessary for obtaining the equisignal fan produces then, however, sudden phase shifts just in the equisignal zone making it considerably wider than desired.[3,5,20]

This disadvantage is avoided when a central radiator, fed with the same carrier, is put between the two outer antennas. The equisignal zones are then formed in those directions where the directive pattern of the two outer antennas approaches zero and only the unkeyed central radiator is effective. The combination of three radiators reduces the number of side lobes by two and the spacing of the outer antennas has to be doubled for obtaining the original configuration.

For a 10° equisignal to the baseline of the three antennas, the distance between the outer radiators is about 6 wavelengths for three-antenna systems and about 3 wavelengths for two-antenna systems.

In the U.S.A. successful attempts were made, at least at long distances, in suppressing substantially the key clicks in the two-antenna CONSOLAN.[20] The r.f. energy is not fed to the towers through an overhead line as is the case with conventional CONSOL stations, but at reduced driving power either by concentric cable or by FM radio link.

This measure was introduced to prevent a horizontal-polarized undesired feeder radiation on the operating frequency, which was supposed to increase the night error. Until now, however, it could not be confirmed that undesired feeder radiation is the reason for the increased bearing error at night, though without doubt this error is caused by a combination of ground and sky waves within the critical range of approximately 400 n.m. from the station. The two towers are fed via phase-stabilized linear amplifiers.

The increase in accuracy by the use of a multilobe pattern leads to an ambiguity of the equisignal zones. For a spacing of about 6 wavelengths between the outer radiators of a three-antenna system the minimum spacing between equivalent sectors is about 20°; the same refers to two-tower CONSOLAN stations with a tower spacing of 3λ. This ambiguity is not objectionable for a long-range navigation system. The sector the observer is actually in, can easily be determined by simple radio direction-finding methods. Besides that, the approximate position will nearly always be known from dead reckoning.

The frequency band of 300 kc/s was chosen at the time of the CONSOL development because it was the common range of the existing receivers, marine and air. Today this range is internationally adopted for radio beacons. Two of the CONSOL stations established after the war operate on about 250 kc/s, two CONSOLAN stations on 190 kc/s (see Table 1). Without doubt the 100 kc/s band would give for CONSOL the same navigational advantage as for other long-range systems. These advantages are larger ground-wave range and more stable reflections from the ionosphere. As, however, the standard airborne and many shipborne receivers have no long-wave range, a special receiver would be required, thus taking away one of the substantial practical advantages offered by CONSOL.

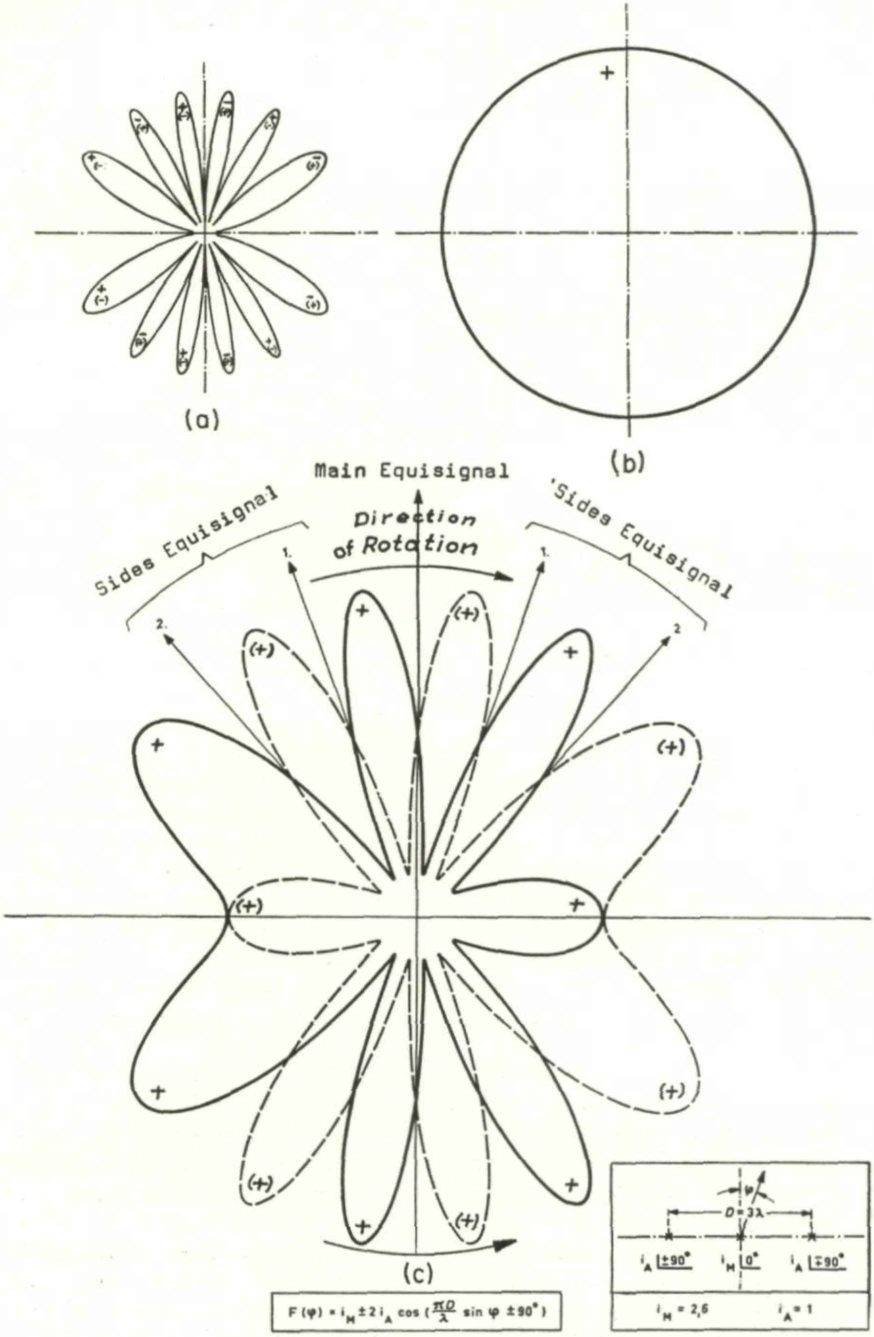

Fig. 4. Azimuth type pattern of a three mast installation, mast spacing $D = 3\lambda$
4a. Side antenna pattern 4b. Central antenna pattern 4c. Combined pattern

3. ACCURACY AND RANGE

The accuracy of CONSOL is limited firstly by the ability of the observer to identify the characters on either side of the equisignal zone, secondly by the number of steps (keyed signals) subdividing the smallest sector.

The limit for aural identification of periodical signals superimposed on a continuous carrier is given at an amplitude ratio of about 5 per cent. From that follows theoretically an observation accuracy of $\pm 0.1°$ within a 10° sector (Fig. 5).

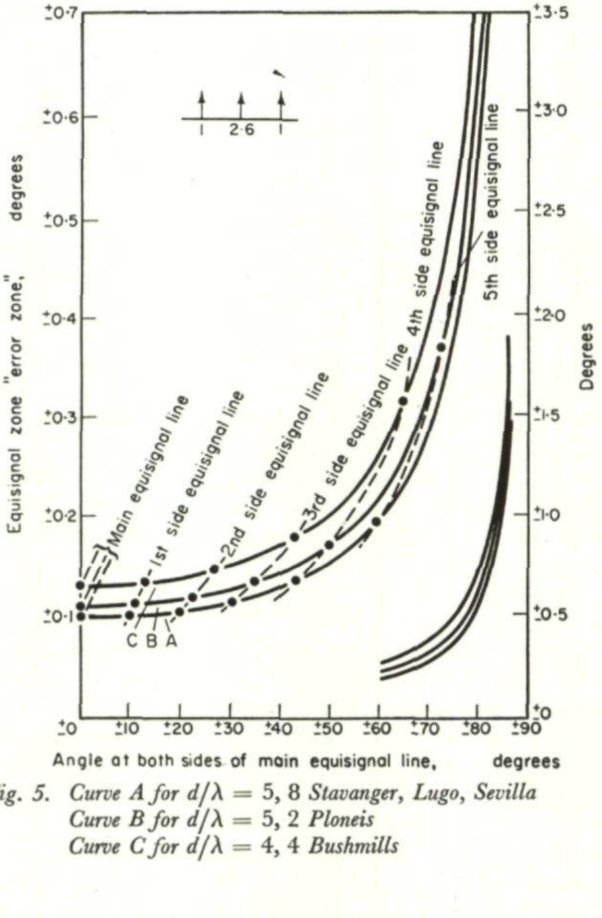

Fig. 5. Curve A for $d/\lambda = 5, 8$ Stavanger, Lugo, Sevilla
Curve B for $d/\lambda = 5, 2$ Ploneis
Curve C for $d/\lambda = 4, 4$ Bushmills

The number of 60 characters (steps) per second limits the possible accuracy geometrically to $\pm \frac{1}{2}°$ within a 10° sector normal to the line of aerials. Lesser accuracies are obtained for other directions due to the increasing width of the sectors proportional to the angle from the normal. The decrease in accuracy corresponds directly to the width of a sector. Under average atmospheric noise conditions the standard deviations observed are greater than those following from the system geometry.[9]

The practical values for daytime operation are:

for 50 per cent of the observations $\pm 0.2^\circ$ corresponding to 0.3 per cent of the distance,

for 95 per cent of the observations $\pm 0.6^\circ$ corresponding to 1 per cent of the distance.

The values are valid for ground-wave propagation that prevails also during night-time for distances up to 200 n.m. At distances between 200 and 450 n.m., especially at night, bearing fluctuations occur due to the interference of sky and ground waves. Sky-wave correction curves were published by British authors.[3]

The corrections read therefrom have to be applied to the arithmetic mean value of several observations. These calculated curves show a maximum for the correction at about 400 n.m. depending on the azimuth referred to the normal to the line of aerials. The thus estimated night error is about 3 characters between 10° and 25°, 6 characters between 26° and 45° and 8 characters between 46° and 70°. Beyond 450 n.m. where the sky wave is dominating, the accuracy increases again up to values similar to those valid for undisturbed ground-wave propagation.

A theory of this problem was given by Kümmich: " Der Nachteffekt bei dem Navigationsverfahren CONSOL "[10] (the night error and its influence on the navigation system CONSOL). According to this theory the correction factors mentioned above and the r.m.s.-errors (standard deviation σ) have approximately the same angle and distance dependence. The magnitudes of both are also about the same. Systematic measurements of the frequency and the magnitude of these deviations were made during recent years by the Deutsches Hydrographisches Institut (DHI) (German Hydrographic Institute) for some sectors in the service area of operating CONSOL stations.[16] The objective of these measurements is the practical investigation of theoretical correction curves and standard deviations. The work is not yet completed.

Other publications[11] indicate the following standard deviations for 95 per cent of the observations: At day ± 1, at night between ± 1 and ± 2 characters. The night values apply within distances between 20 and 150 n.m. and beyond 550 n.m. Between 250 and 450 n.m. deviations of ± 4 to ± 7 characters may occur with a maximum at 350 n.m.

Keeling[12] used the following standard deviations as basis for range vs. accuracy curves:

at day on sea	1	character	for all distances
at night on sea	1	,,	from 0–100 n.m.
	2	,,	,, 100–200 n.m.
	3½	,,	,, 200–300 n.m.
	6½	,,	,, 300–400 n.m.
	6	,,	,, 400–500 n.m.
	3½	,,	,, 500–600 n.m.
	2	,,	around 600 n.m.
	1		considerably more than 600 n.m.

For further tables with data gained by experience see ref. 17; an evaluation of approximately 150,000 observations made on two German Sonne installations (propagation over land) was made in England after the war

and published together with extensive own investigations over land and sea.[18]

The maximum useful range of CONSOL is dependent on the propagation conditions (across sea or across land), the atmospheric noise level and the receiver bandwidth. For these reasons the published values show considerable variations. This is also due to the differences in the definition of the term " range ".

Average values:

across sea:	at day	700–1200 n.m.
	at night	700–1500 n.m.
across land:	at day	500–700 n.m.
	at night	900–1200 n.m.

The keying cycle of CONSOL is very slow (at present generally 60 characters within 30 sec). Therefore narrow bandwidth receivers can be used to improve considerably the signal-to-noise ratio and, hence, the useful range. This was proven by French experiments: Ranges of up to 2600 n.m. were obtained with a special receiver of only 100 c/s bandwidth.[6,22,23]

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The radio coordinates supplied by CONSOL are radial lines of position with true reference direction. The indication is not continuous, but has to be determined periodically by counting the number of characters until the equisignal zone is observed every 60 sec (older equipment) or every 45 sec (modern equipment) corresponding to the keying cycle (cf. table). The geographical position is obtained from special maps overprinted with position lines corresponding to selected CONSOL counts or from auxiliary tables.[14] A fix is determined by the intersection of the radial position obtained from two CONSOL stations.

For direct air navigation without reference to a map, CONSOL is only suitable in the special case of flying directly to or from a station and keeping the plane on a line with a fixed number of characters.

Concerning the operation of the receiver, care has to be taken only to avoid suppression or distortion of signals by overload. Normally that is avoided by automatic gain control. Besides that, the indication is independent of the field strength or received power. Ambiguities which amount to 20° around the normal to the aerials have to be eliminated either by dead reckoning or by taking the bearing of the station.

A position line is obtained by counting the number of characters which should be observed through earphones. Automatic counters were proposed, but they have not as yet been used in practice.[19]

5. GROUND STATION AND AIRBORNE (SHIPBORNE) EQUIPMENT

CONSOL Ground Station

Normal transmitter, power approximately 1.5–5 kW, with a keying and goniometer unit; three 100 m towers, with counterpoise, installed in a straight line at a distance from each other of approximately 2.8 wavelengths, r.f. energy fed to the outer antennas via overhead lines; monitor

station close to the normal to the line of aerials at a distance of approximately 4 km from the central aerial mast. Information on costs is presented in Table 4.3.

Only engineering information is available on CONSOLAN. Stations operating in the 190 kc/s range have a power of 6 kW per tower; the tower spacing is 3 wavelengths; tower height 200 m with top loading; the counterpoise seems to consist of 120 copper strips of $\frac{1}{4}$ wavelength; the monitoring station is located on the line connecting the towers. For propagation over sea, a field strength of 50 μV/m is obtained at a distance of 1500 km, and of 10 μV/m at 2100 km.

CONSOL Site Requirements

Plane strip of land of approximately 1×6 km for a wavelength of 1.000 m, ground of maximum uniformity 1 km diameter around the individual aerials; aerial mast bases at approximately equal height above sea level.

For CONSOLAN very stringent requirements concerning the ground conductivity and planeness of terrain must be satisfied.

Airborne (Shipborne) Equipment

Normal radio receiver, if possible, provided with bandwidth control down to 200 c/s, receiving aerial and immediate vicinity uncritical, however, preference should be given to vertical aerials.

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2.03. NAVAGLOBE

T. v. Hauteville

Navaglobe is a long-range rotating radio beacon operating in the 100 kc/s frequency band. The principal features are:

(*a*) Full compatibility with the short-range system VOR, achieved by using the same basic principles (see Chapter 2.04). The system supplies direct-bearing information to and from the ground station. The measured values are read from the same instrument as used for VOR.

(*b*) The ground installation comprises only one site. That simplifies the problem of site selection.

The development of this low-frequency rotating radio beacon was started 1946–47 in cooperation between the USAF and the ITT Laboratories, Nutley, N.J. The system was demonstrated before a greater public in 1954 on the occasion of an ICAO Conference.

Very early it was decided to supplement the system by additional airborne distance measuring equipment, thus obtaining a complete rho–theta system. This long-range rho–theta system that incorporates Navaglobe for the bearing determination is known as Navarho (see Chapter 2.07). At the present state of the Navarho development and on account of the requirements specified by the ICAO for long-range navigation systems (see: Final Report ICAO, 2nd Air Navigation Conference, September 1955, Report 7625, Document 2553–COT/26) it is no longer intended to introduce Navaglobe which supplies only bearing information.

For the technical description reference is made to the description of Navarho in Chapter 2.07, because the bearing measuring part of the Navarho is essentially the same as the original Navaglobe.

2.04. VOR-SYSTEM

The Very High Frequency Omni-directional Range System

K. Bärner

1. GENERAL INTRODUCTION

Omni-directional ranges (Omniranges) operating in the low-frequency band have been known and used since 1908 (Telefunken Kompass[17]). The radio lines of position obtained from such omni-directional ranges can be utilized by simple airborne equipment. With the transition to v.h.f. techniques—in order to overcome interferences by statics and night effect—the v.h.f. omni-directional range (VOR) was developed in the U.S.A. and is still operating on the same principle today, although a variety of different constructions are in use.

The VOR system indicates the magnetic bearing of the omnirange (Fig. 1) to the pilot by means of an omni-bearing indicator. For indication, however, the same meter as for the radio compass, i.e. the radio-magnetic indicator (RMI), may be used as well. On a flight toward or away from the Omnirange the deviation from a line of position selected by means of the omni-bearing selector (OBS)* may be indicated by a deviation indicator (cross-pointer instrument) whose pointer is deflected either to the left or to the right, An additional to/from indicator provided on the omni-bearing selector shows whether the bearing indicated on the omni-bearing selector is measured *from* the VOR to the aircraft or from the aircraft *to* the VOR.

It was originally intended to combine VOR with a DME (Distance Measuring Equipment). Such a navigation system would have enabled the pilot to fix his position by reference to one ground station only. The plans were influenced, however, by the development of the TACAN system, which was intended for military purposes, in such a manner that the DME was disregarded. The TACAN system is similar to the VOR–DME combination. Instead VOR was combined with the TACAN system (cf. Description of Operation, Chapter 2.05). This new system is called the VORTAC system.

Although distance information is not yet provided by the VOR system, some hundred VOR installations are operating in various countries, because, located at or close to the destination, they allow for an easy navigation with the flight following a radial line—course deviations being displayed by a zero indicator (cross-pointer) and the required azimuth being preselected.

The r.f. energy emitted by VOR depends on the application (installation on an airport or along an airway) and varies between 50 and 200 W.

* Often also referred to as " Course Selector " which may give rise to errors.

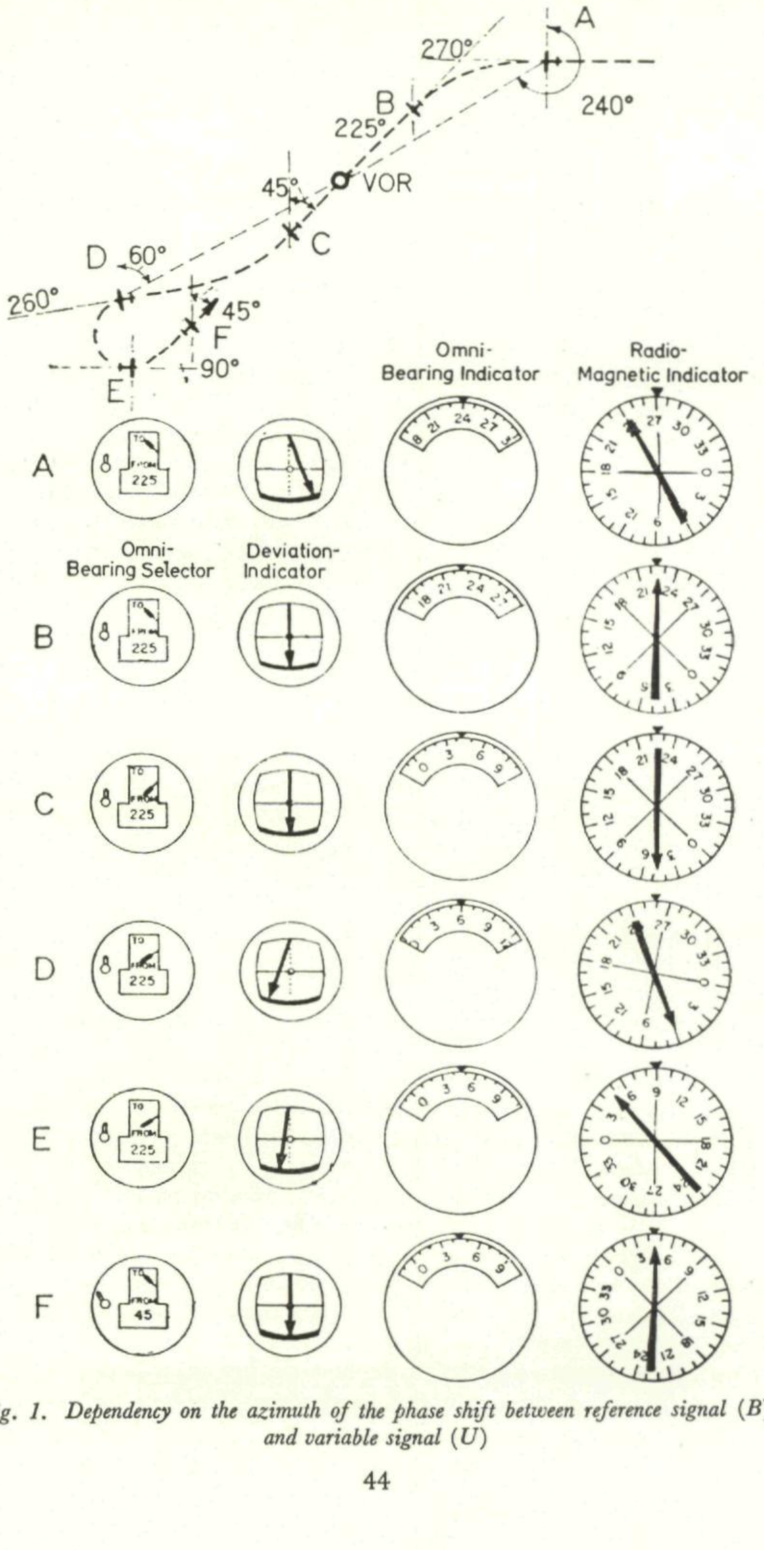

Fig. 1. Dependency on the azimuth of the phase shift between reference signal (B) and variable signal (U)

Constructions differ primarily in the antenna system (cage-type antenna, slotted antenna, Alford antenna array). The coverage obtainable corresponds to the optical line of sight plus allowance for tropospheric refraction. Coverage is therefore dependent upon the altitude of the aircraft.

2. PRINCIPLES OF OPERATION

The principle of the VOR system[1–10] is based on phase comparison between two audio-frequency oscillations of equal frequency (30 c/s) associated with the radio-frequency radiation. In order to separate the two wave-trains of equal frequency in the receiver a special trick is used. The greater portion (approximately 90 per cent) of the r.f. energy generated is emitted by an omni-directional antenna (*B* of Fig. 2) and is amplitude modulated with 10 kc/s (9960 c/s) whereby the sub-carrier in turn is

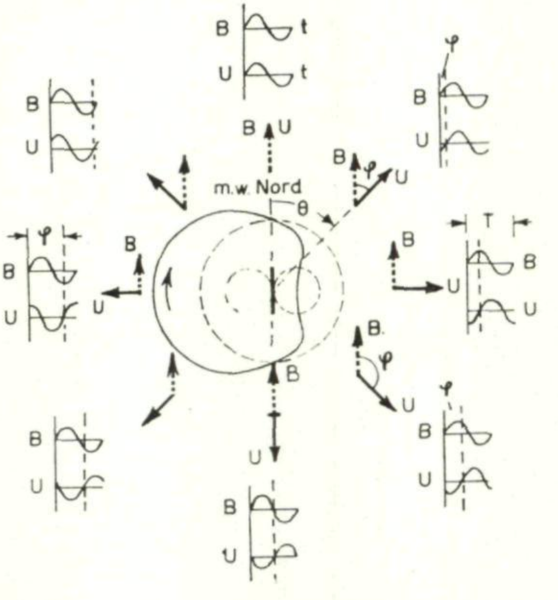

Fig. 2. Airborne instrument indications illustrating a flight path

frequency modulated with 30 c/s (reference phase signal). A small portion (approximately 10 per cent) of the r.f. energy generated, however, is not modulated and is emitted by a directional antenna (figure-of-eight radiation pattern, *U* of Fig. 2). Both partial r.f. fields are phase locked. Since the directional pattern is rotated at a speed of 30 rev/sec, for instance by mechanical rotation of the respective dipole, the field is amplitude modulated at 30 c/s in the point of reception and its phase aspect varies with the bearing of the receiver (variable phase signal) (Fig. 2).

In the aircraft a receiver is used which is applicable to both VOR and ILS. In this unit (see Fig. 3) for VOR reception the 30 c/s signal of the 10 kc/s subcarrier is recovered from the r.f. signal received and, at the same time, the 30 c/s signal of the azimuth-depending amplitude modulation is detected. The phase difference between both signals is presented by

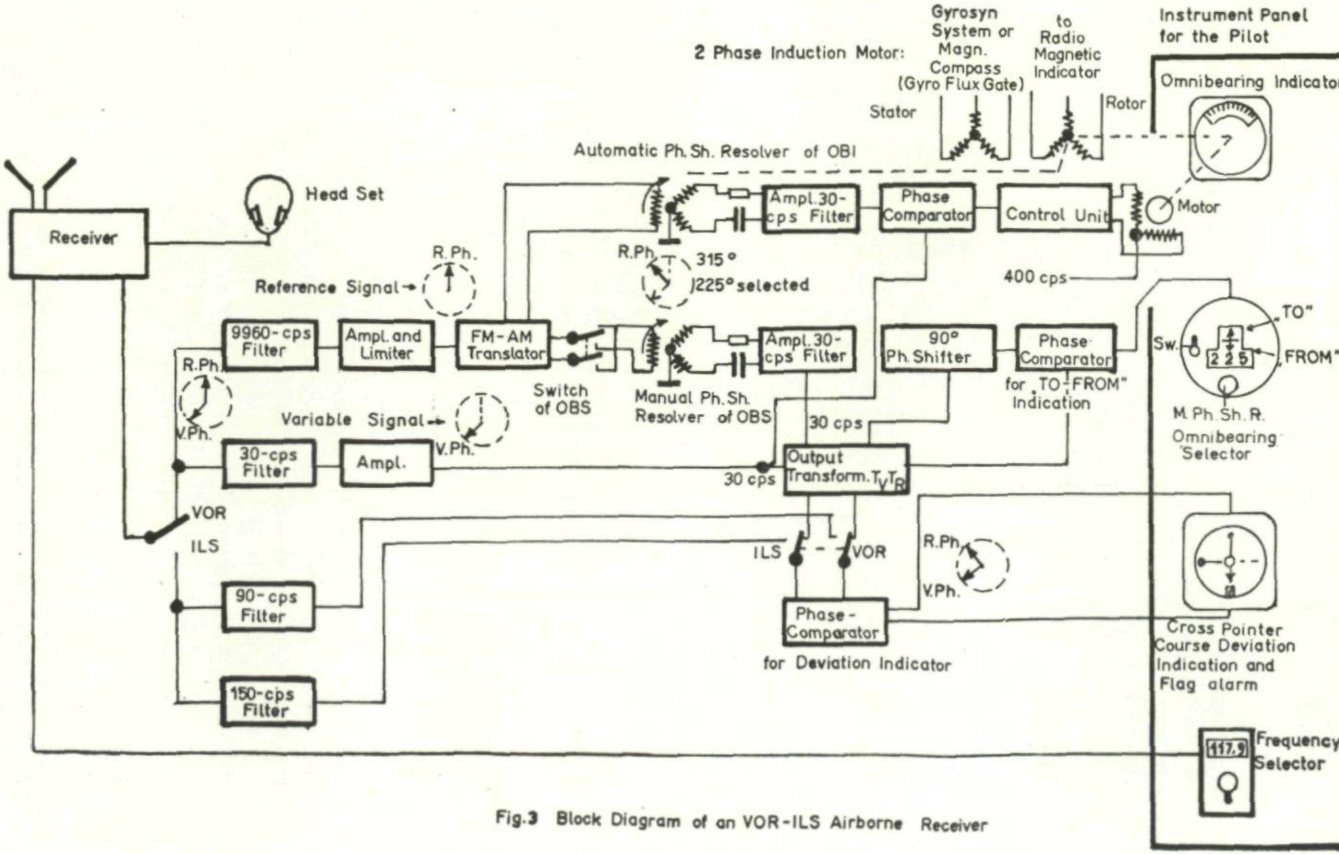

Fig. 3 Block Diagram of an VOR-ILS Airborne Receiver

means of a phase meter and an automatic device on the omni-bearing indicator. If the phase angle is zero with respect to north, the phase angle indicated will be equal to the azimuth.

The automatic device comprises a servo-driven phase selector (automatic resolver) incorporated in the omni-bearing indicator which is coupled to the 360° scale and a control unit (manual resolver) by means of which the servo motor of the omni-bearing indicator is operated until zero is indicated by the phase meter. The omni-bearing indicator then indicates the bearing of the aircraft relative to the VOR station on its 360° scale. For reading, a fixed mark indicating magnetic north is provided at the top of the instrument. A radio-magnetic indicator (RMI) can be connected by means of a synchron motor, whose rotor is also coupled to the omni-bearing indicator servo motor. Thus the position of the radio-magnetic indicator pointer coincides with that of the omni-bearing indicator. In order to obtain coincidence between the radio-magnetic indicator and radio compass indication—the fixed triangular mark on the radio-magnetic indicator must indicate the longitudinal axis of the aircraft and not magnetic north—the angle between magnetic north and VOR station* will have to be corrected by the compass data; it is only then that the azimuth can be read from the 360° scale. For this purpose, the stator system of the synchro motor of the omni-bearing indicator is fed by the synchro generator of a magnetic compass. Thus the zero position of the omni-bearing indicator is changed with the zero position of the magnetic compass (magnetic north). Then the following conditions are indicated by the radio-magnetic indicator: The compass course, i.e. the angle between magnetic north and the longitudinal axis of the aircraft (scale value indicated by the mark, Fig. 1); the magnetic bearing of the VOR (scale value indicated by the pointer); and the angle between the longitudinal axis of the aircraft and the VOR (pointer on mark). When a deviation indicator (cross-pointer instrument) is used, a phase selector incorporated in the omni-bearing selector and a separate phase mater (Fig. 3) are employed.

The phase meter is connected directly with the deviation indicator, which indicates zero (centre position of the pointer) when the phase of the variable signal coincides with the phase of the reference signal which is adjusted by the manually operated phase selector. Since the phase of the variable signal can be shifted over a 360° range, any desired azimuth can be selected.

When the field strength received is too small to secure a reliable operation of the phase meters, the cross-pointer instrument will signal this condition (flag alarm).

An additional phase measuring facility (Fig. 3) compares the angular value received from the VOR with the bearing set manually on the omni-bearing selector. The result of this comparison is indicated on the to/from indicator. It is the purpose of this to/from indicator to show the pilot whether the bearing indication, which is obtained from the deviation indicator together with the value set on the omni-bearing selector, indicates the direction *from* the station to the aircraft, or the direction from the aircraft

* As transmitted from the omni-bearing indicator.

to the station. Since the VOR bearing is independent of the direction of the longitudinal axis of the aircraft (heading) (as contrasted with the bearing taken with direction-finders on board) there is no direct relationship between the to/from indication and the heading. Therefore, the indication remains constant, e.g. from, if a VOR radial is set on the OBS, whether the aircraft is flying towards or away from the station or just passing it. When, however, the correct relationship between omni-bearing indication and heading has been established, which is usually the case when the VOR is used as reference on airways, the to/from indication is valid in the same way for the heading and remains to be correct even when the aircraft has been flown over the station. If, for instance, the indication during approach was *to* it is automatically changed into *from* when the aircraft has been flown over the station, provided the OBS setting remains unchanged.

In order to achieve quickly coincidence of VOR reading and heading, a separate change-over switch is provided by means of which the bearing value can be changed by 180°. The to/from indication is reversed at the same time (cf. Fig. 1).

Doubts as to the existing relationship between heading and bearing can be overcome easily by comparing the bearing indication with the compass indication. If the compass system fails, the relationship between the to/from reading and the heading can also be read from the deflection of the cross-pointer instrument; if the to/from indication coincides with the heading, the pointer of the cross-pointer instrument is deflected to the right if there is a deviation to the left of the intended line of position; pointer deflection is to the left in the case of a left-hand deviation.

The system is to operate in the 108–118 Mc/s frequency band so that 80 channels are available with a channel spacing of 100 kc/s. In the 108–112 Mc/s range only such frequencies are used which correspond to even-numbered multiples of 100 kc/s, e.g. 108.2 Mc/s, 108.4 Mc/s, etc. (i.e. 20 channels); the odd-numbered multiples, e.g. 108.1 Mc/s, 108.3 Mc/s, etc., are reserved for the instrument landing system. In the range of 112–118 Mc/s all frequencies spaced by 100 kc/s are used (60 channels). These channels can be distributed over a sufficiently large area so that interference of VORs operating on the same frequency in adjacent areas will not occur in practice (cf. section 3.3).

3. RANGE AND ACCURACY

3.1. *Range*

The VOR system is a short-range navigation system. The range is dependent upon the altitude of the aircraft. It is equal to the range of very high frequencies (optical sight) plus approximately 15–20 per cent. Thus the following ranges are obtainable:

at an altitude of 1000 ft (300 m) — 50 n.m. (92 km)
at an altitude of 5000 ft (1500 m) — 92 n.m. (170 km)
at an altitude of 20,000 ft (6000 m)—182 n.m. (335 km)
at an altitude of 30,000 ft (9000 m)—220 n.m. (410 km)

The following reliable ranges were measured: 140 km (75 n.m.) at an

altitude of 3000 ft (900 m) or 170 km (95 n.m.) at an altitude of 5000 ft (1500 m).[10]

For aircraft operating at lower altitudes (helicopters, sports aircraft) the ranges will be reduced (at an altitude of 500 ft corresponding to 150 m approximately 60–70 km).

3.2. *Accuracy*

The overall error[5] comprises the following systematic errors:

ground station error,
airborne equipment error.

Each of these errors comprises:

equipment and antenna error,
site or location error resp.

The error curve of a VOR is established by orbit flights around the VOR and by comparing the azimuth indication to the nominal values (Annex 10, ICAO). It is of the semi-circular, quadrantal, sextant or irregular type with positive and negative deviations from the nominal value of the azimuth. With regard to the positive or negative maximum respectively, or with respect to the maximum error difference (difference between positive and negative maximum) certain limits are laid down.

The maximum error of the equipment including the antenna permitted by ICAO Annex 10 is $\pm 2°$ at a distance from the antenna of 4 times the wavelengths, and at an elevation of 0°–40°. The maximum ground station error (equipment, antenna and site error) should not exceed $\pm 3.5°$. The following empirical values of the maximum error are available:

Ground station: $\pm 1.58°$ (average of 25 ground stations)[9]

$\pm 2.5°$ [12]

$\pm 2.2°$ (average of eight ground stations, 20 measurements made within 3 years, 1956–58, of the same station after technical modifications only: maximum error of the poorest station $\pm 3.5°$, of the best station $\pm 0.8°$). BFS, Federal Republic of Germany.

$\pm 1.4°$ (average of 19 VORs, altogether 190 error contours; achieved by improvements in the aerial and ground checks). 1961, BFS, Federal Republic of Germany.

$\pm 2.0°$ (at 95 per cent probability, $\pm 3.5°$ at 99–97 per cent probability. The data of 276 VOR installations were processed by statistical methods. The error distribution complies with Gauss error distribution law).[19]

Airborne equipment (under normal operating conditions):

$\pm 0.75°$ Marconi receiver AD704[13]

$< \pm 1.2°$ Collins receiver 51R–2

$\pm 1.8°$ ... 4.5°[12] without information of type*

$\pm 2.0°$ ... 3.0° minor Narco and Lear receivers.

These errors can be kept constant and those owing to the ground station

* The airborne equipment error is dependent upon the maintenance of the equipment.

may be published with regard to distinguished directions (for instance, airways).

In case many VOR stations are in operation, it would be more reasonable to combine these errors with the second class of errors, the random errors, and thus to determine the error of the VOR system. This would also be recommendable with regard to the propagation errors which are for one part systematic errors (depending upon the very high frequency used) and for the other part random errors. In this connection the *en route* error should be particularly mentioned, which occurs due to reflections from hills, mountain ranges and lakes. This error occurs immediately in front or in the back of the interfering object and is indicated by relatively rapid deflections of the deviation indicator (" scalloping "). The interval between variations depends upon the course relative to the interference field. This should be distinguished from the error produced by reflecting objects in the vicinity of the VOR ground station, which appears as a bend of some kilometers in length in the line of position.[20] The amplitude of such scallopings may amount to $\pm$ 3–5° in mountainous country.[22]

The random errors comprise errors caused by:

variations of the supply voltage (ground and airborne equipment),
variations in the aerial, phase deviations of the r.f. partial fields,
variations of the r.f. power (propagation, reflections),
temperature changes,
receiver adjustment,
inaccurate reading.

The overall VOR system error (ground station and airborne equipment errors) as obtained by tests performed with commercial aircraft was[8]:

at 68 per cent of the tests $< \pm 1.7°$ (standard deviation)
at 95 per cent of the tests $< \pm 3.4°$
at 99.7 per cent of the tests $< \pm 5.1°$.

The total number of observations is not known. Other authorities[9] indicate an accuracy of the VOR system of:

$$< \pm 4.8° \text{ at 99.7 per cent of the tests}$$

These figures are based on 6355 observations. During these tests, which were also carried out with commercial aircraft, the direction indicated over known fixed ground points was compared with the true direction whereat high-quality airborne receivers were used. The maximum ground station error was $\pm$ 1.58° (average of 25 stations).

Recent investigations[21] showed an overall error of $\pm$ 1.54° when receivers of the highest quality class were used, and of 2.06° when receivers of a lower quality class were employed, the probability being 95 per cent in either case. The reduction in the error is due to improvements in the ground stations and their monitoring facilities (error of ground station $\pm$ 1.53° at a 95 per cent probability, as measured on 196 VORs; 1956: $\pm$ 2.15 per cent; 1954: $\pm$ 2.48° at 95 per cent) and to improvements in the airborne receiver. Since the standard deviation of 0.104° or 0.694° resp. of the two receiver categories under standard test conditions should be 0.5° or 1° resp. for all practical purposes, the overall error is $\pm$ 1.83° or 2.52° resp.

Thus all types of error, i.e. both systematic errors (ground and airborne equipment) and random errors, are treated by statistical methods, therefore

the overall error of the VOR system comprises the observation error of visual fixing.

3.3. *Ambiguity*

Indication is unambiguous when an omni-bearing indicator is used. When, however, an omni-bearing selector and deviation indicator is used, indication is ambiguous in that an opposite direction relative to the ground station results in equal measuring data and, hence, course data. This ambiguity is eliminated by the to/from indicator.

Two VORs operating on the same frequency should be spaced sufficiently far apart so that the zone of uncertainty caused by interference is sufficiently high above ground.

The geographical separation of VOR stations operating on the same frequency is indicated in the table of Add. 32, Annex 10 (ICAO) :

Selection	*S* (*dB/n.m.*)	*K* (*dB*)	*Minimum Geographical Separation Between Stations* (*n.m.*)
VOR_1—VOR_2	0.2	0	500
VOR_1—VOR_2	0.2	0	500
VOR_2—VOR_2	0.3	0	327
VOR_B—VOR_B	0.5	0	90
VOR_1—VOR_B	0.2	6	470
VOR_2—VOR_B	0.3	6	307

S = slope of the curve indicating the field strength-to-distance ratio for constant height (dB/n.m.).

K = power ratio of 2 VORs with equal or different nominal ranges.

VOR_1 and VOR_2 are of the same type (Type A VOR) but of different service ranges and a height utilization as follows :

VOR_1 200 n.m. 12,000 m (40,000 ft)
VOR_2 130 n.m. 6000 m (20,000 ft)
VOR_B an equipment of reduced power (Type B VOR)
up to 25 n.m. 3000 m (10,000 ft)

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The pilot is provided with continuous course line information toward or away from the VOR station as line of position when an omni-bearing indicator is used, or with zero indication when an omni-bearing selector is used (cf. sections 1 and 2).

For establishing a fix either a distance measuring equipment (DME) or another line of position obtained from a second VOR is required. A period of approximately 2 min is required for establishing a fix. It is possible to employ computers and visual display which would eliminate the necessity of drawing the lines of position and thus simplify position fixing. Normally the airborne equipment is operated by the pilot without assistance. No special training is required.

For evaluation the following equipment is required:

table of VOR frequencies,

normal charts on which the VOR stations are indicated (no special charts are necessary).

The VOR system is suitable for coupling when the flight follows a radial line of position.

Maintenance of the airborne equipment is accomplished by the ground staff. The calibration of the equipment will have to be checked thoroughly and periodically. However, the operational reliability of the equipment is of a very high order. Commercial aircraft usually are equipped with two airborne installations. A VOR station can accommodate an unlimited number of users.

Since VOR ground stations are operating automatically, they do not require a permanently present staff; however, the equipment has to be checked periodically (weekly) by a radio engineer who is familiar with the equipment. The technical staff must be trained especially for their jobs in order to be able to work efficiently. The circuitry employed both in the ground station and in the airborne equipment is the commonly used one in modern v.h.f. techniques.

The operational reliability is in compliance with the technical and operational requirements. The equipment at present in use (dual equipment) meets the tolerance requirements at continuous day and night operation and under normal operating conditions without exceeding the maintenance expenditure mentioned above. (Frequency tolerance of the r.f. generator $\pm 5 \times 10^{-5}$, that of the 60-cycle generator $\pm 3 \times 10^{-3}$.)

The most sensitive part of the ground installation is the antenna insert containing the rotating dipole with drive and tone wheel whose service life hitherto has been 0.5 to 1 year (experience of the BFS). Other authorities claim a service life of several years.

In case of ground station failures automatic change-over to the standby transmitter results. For 50W TVORs a manually operated remote switch-over facility is provided at the control point of the airport. Observance of the zero phase angle in the direction of magnetic north is secured by regular maintenance.

As soon as the ground station does not operate within the determined tolerances, or the receiver input voltage falls below the permissible minimum value, flag alarm is given on the cross-pointer instrument.

Besides the normal navigational information an arbitrary adjustable identification signal is radiated without impairing the position-fixing procedure. Furthermore a voice communication channel is provided to transmit in the same manner both general or meteorological information periodically, e.g. automatically, or on request, without impairing the position-fixing procedure.

5. EXPENDITURE

5.1. *Ground Stations*

For the complete coverage of a larger area a suitable number of ground stations will have to be provided in compliance with ICAO regulations as mentioned in Sect. 3, para. 3. The existing and planned VOR station

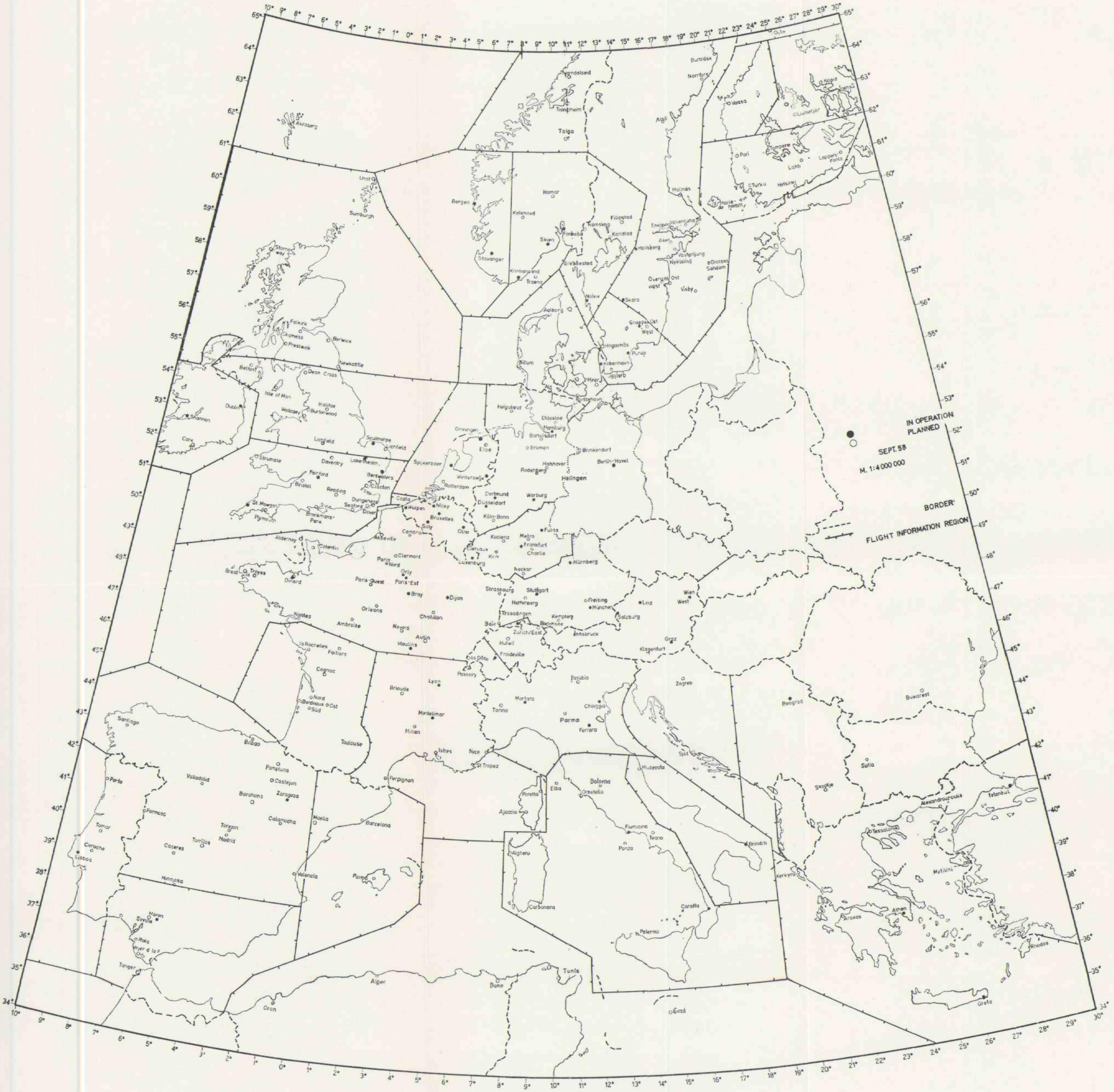

Fig. 4. Map of existing or planned VOR stations (Europe)

network is illustrated in Fig. 4 (EUM Frequency Coordinating Body Meeting (FCB), Paris, Sept. 1958).

5.1.1. *Technical data.* The ground stations are of two types:

normal VOR (200W),

installed load 7 kVA, and

low-powered VOR of 50W, designed for installation on an airport (TVOR), installed load 5 kVA.

The equipment is housed in a building of approximately 10 m diameter, on the roof of which the antenna is mounted.

5.1.2. *Dimensions and weights.* The dimensions and weights (including standby equipment) of a modern 200W station with cage antenna are:

Equipment	*Height (in.)*	*Width (in.)*	*Depth (in.)*	*Weight (lb)*
Four racks, complete	447	607	188	3750
Antenna	1400	227	227	77
Operator's station (remote control unit, desk set)	71	76	76	28,7
Tower box (terminal box for desk set)	173	109	109	112

A 50W station has only two racks (including standby equipment) since the racks of the power amplifiers are omitted. The weight is reduced accordingly.

5.1.3. *Prices.* The price of a 200W VOR station including assembly is approximately DM 140.000; that of the 50W station approximately DM 97.000. To this must be added the cost of approximately DM 60.000 for the VOR building including power supply installation. A similar station manufactured in the U.S.A. (with slotted antenna) including transmitter building of corrugated steel would cost in Germany DM 100.000 (200W) or DM 87.000 (50W) respectively.

5.1.4. *Terrain, siting and installation requirements, antenna.* A terrain of approximately 250 m^2 should be leased. No obstructions are allowed up to a distance of 65 m (300 ft) from the station. Only short cut grass may be tolerated in this area.

The siting requirements are outlined in Annex 10, ICAO. The station should be erected on the highest possible point to obtain the greatest line-of-sight coverage. The terrain should be level or should not slope away more than 4 per cent up to a distance of at least 300 m (1000 ft) or, better, 600 m (2000 ft) around the station, but in any case the site contours should be circular with respect to the antenna array to a radius of at least 300 m (1000 ft).

The height of wire lines or fences should not exceed a vertical angle of

1.5° relative to the ground or 0.5° relative to the antenna base. These values may be increased by a factor of 1.5 when the lines or fences are arranged radially to the antenna or subtend an azimuth angle of not more than 10°.

Single trees of normal extension and up to a height of 9 m (30 ft) are permissible beyond a distance of 150 m (500 ft) from the station. Groups of trees of a vertical angle of more than 2° are not permitted within 300 m (1000 ft) of the station. It is recommended to secure permission for clearing the terrain of trees up to 600 m (2000 ft) from the station.

Buildings should not be within a radius of 150 m (500 ft), beyond this distance, the vertical angle of solid buildings should not exceed 1.2°. For wooden structures of small horizontal extension with negligible metallic contents the permissible vertical angle may be increased up to 2.5°.

In mountainous terrain the station should be sited on top of the highest elevation and this should be flat or levelled to a radius of at least 45 m (150 ft).[13] In this case the antenna should be installed approximately ½ wavelength above ground in the centre of the graded area and the transmitter building should be erected outside this area at a sufficient distance to be below the optical line-of-sight. No trees, power lines, buildings, etc., should be present above the radio horizon between 45 m (150 ft) and 360 m (1200 ft) from the station. The access roads shall be kept in usable condition.

5.2. *Airborne Equipment*

5.2.1. *Technical data.* For reception normally a VOR–ILS receiver is used (cf. 2). The channels are separated by 100 kc/s at present. The bandwidth required for processing VOR signals is 21 kc/s.

Manufacturer	*Model*	*Sensitivity*	*Frequency Tolerance* (%)	*Power Input*	
				a.c. supply	*d.c. supply*
Marconi	AD 704	3 μV at 6 dB signal-to-noise ratio	$\pm$ 0.0035	80 VA	
Bendix	MN–85	3 μV at 6 dB signal-to-noise ratio (200 mW output power)	$\pm$ 0.01	100 VA	125 VA
Collins	51R–3	3μV at 6 dB signal-to-noise ratio (200 mW output power)	$\pm$ 0.01	115 VA	100 W

The channel separation of other receivers is 50 kc/s (e.g. Collins 51R–4).

5.2.2. *Dimensions, Weights, Prices*

Collins receiver 51R–3 (all prices are listed).

Unit	*Weight (lb)*	*Dimensions (in.)*	*Price (US dollar)*
Receiver with shockmount	32.1	$24\frac{5}{6} \times 4\frac{1}{8} \times 7\frac{3}{4}$	2380
Antenna	5.75	—	200
Control unit	0.8	$3\frac{9}{16} \times 2\frac{1}{4} \times 2\frac{3}{16}$	100
Power supply	8.2	$7\frac{7}{32} \times 7\frac{1}{4} \times 5\frac{1}{8}$	168 from a.c.
			208 from d.c.

Bendix receiver MN–85.

Unit	*Weight (lb)*	*Dimensions (in.)*	*Price (US Dollar)*
Receiver with shockmount	32.00	$26 \times 5.875 \times 9.23$	2440
Antenna	6.2	—	200
Control unit	1.1	$3.06 \times 2.75 \times 3.9$	128
Power supply	8.4	$9.57 \times 8.6 \times 5.6$	172 from a.c.
			236 from d.c.

Instrumentation.

Unit	*Weight (lb)*	*Dimensions (in.)*	*Price (US—Dollar)*
Omni-bearing indicator	2.4	ϕ 3.125, depth 4.19	568
Omni-bearing selector	1.9	ϕ 3.125, depth 6.13	472.80
Deviation indicator	1.1	ϕ 3.156, depth 3.66	180
Radio-magnetic indicator	1.9	ϕ 3.125, depth 4.78	660

The price of a dual installation including instruments is approximately $9500. (list price).

The weight of minor receivers is approximately 5 kg, their price is approximately $2000, with simplified instrumentation (list price). Recently transistorized miniature receivers have been marketed.

5.2.3. *Installation requirements.* The receivers can be installed in the usual manner. The installation costs depend on the type of the aircraft, the weight and the costs of connecting cables on the location of the receiver. The airborne antenna (V dipole) should be located in the vertical plane of symmetry of the aircraft in order to secure a useful polar diagram. Normally it is installed on top of the fuselage.

6. FURTHER DEVELOPMENT (DOPPLER VOR)

VORs sometimes have to be installed on unfavourable sites. To reduce the errors which are due to reflecting objects in the vicinity of VORs (site

errors) the Doppler VOR was developed which allows the use of unaltered airborne equipment in spite of a different technology of the ground station.

The Doppler VOR station has a central aerial on a large metallic surface of 150 ft (45.75 m) in diameter and 50 single aerials arranged in a circle around the central aerial, with the circle diameter being 22 ft = approx. 6.7 m = approx. 2.5λ. The radiation pattern of each aerial is almost circular. The central aerial radiates the major portion of the r.f. energy which is amplitude-modulated with 30 c/s (first r.f. generator). This radiation component thus provides the reference phase in the airborne receiver. The 50 single aerials are energized individually by being fed consecutively with a frequency which is by 9960 c/s higher (second generator). Hence, for the purpose of explaining the principle, they may be replaced by a single rotating aerial. This fictitious source of radiation is rotated at a speed of 30 rev/sec. For this reason and because of the spacing (approximately 2.5λ) of the apparently rotating aerial, the radiation from this aerial (second r.f. generator), which is by 9960 c/s higher than that of the central aerial, is frequency modulated with a frequency deviation of $\pm$ 480 c/s. The phase of the 30 c/s modulation of this frequency-modulated oscillation (variable phase) depends directly on the directional angle of the receiver relative to the station. The airborne receiver thus receives a reference signal by screening the amplitude-modulated portion of the carrier frequency (central aerial) and a phase-variable signal by demodulation of the auxiliary carrier frequency of 9960 c/s which is frequency-modulated by 30 c/s.

Extensive studies were made of such installations in the U.S.A.[24] Under comparable site conditions the site errors or the bends respectively were reduced to one-quarter to one-seventh of their original magnitude for most bearings (e.g. Charleston VOR from $\pm$ 2.8°–0.4°). The theory behind this system including also the error theory are contained in refs. 25 and 26.

The technical requirements of a Doppler VOR, especially for the aerial system, are considerably greater than those for a conventional VOR. Also a larger area is required. The environmental requirements (protective zones) are reduced. The system is not yet commercially available. Hence, no prices can be given.

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2.05. TACAN

(TACtical Air Navigation)

T. v. Hauteville

1. INTRODUCTION

TACAN is a 1000 Mc/s Rho–Theta system for short-range navigation. It has been developed in the U.S.A. since 1950 by Federal Telecommunication Laboratories at the suggestion of the U.S. Navy and U.S. Air Force and in cooperation with them. Preliminary work had been done since 1945. Kept secret until 1955, when the system had been tested and was introduced in the U.S. Air Force, the first public information was disclosed on the occasion of the TACAN symposium held in Washington in autumn 1955. In the meantime TACAN was standardized as the military short-range navigation system of the NATO countries.

Within the framework of the " common system " of coordinated military and civil air traffic control it has been decided in the U.S.A. to extend the application of TACAN considerably and to install TACAN ground stations for *en route* traffic control on existing or newly planned VOR sites. Until 1965 it is intended to have a total of 1230 VOR/TACAN ground stations for air traffic control along the American airways (Fig. 4). This combined system is called VORTAC (see system description 2.06).

VORTAC allows civil aircraft to obtain bearing information in the 100 Mc/s band as with VOR. In addition a plane equipped with DMET (Distance Measuring Equipment TACAN) can measure the distance from the ground station. Military planes equipped with complete TACAN airborne sets measure bearing and distance by means of this TACAN ground station equipment and do not use the VOR bearing information.

For the further development of TACAN the following stages are intended :

1.1. *The Application of the System to Instrument Landing*

1.1.1. Combination of the present conventional ILS systems incorporating the 100 Mc/s localizer and the 300 Mc/s glide path transmitter with a TACAN compatible DME ground station for distance measurement. This version is called ILS–DMET.

1.2.2. Also being tested are arrangements, where, by multiple use of a TACAN r.f. channel, the localizer and glide path information are transmitted simultaneously with the distance measuring signals and all three are received and evaluated by the airborne TACAN equipment. System designation : TACAN–ILS.

1.2. *TACAN Date Link*

The TACAN Data Link now being tested allows simultaneously and without mutual interference on the same r.f. channel the transmission of bearing and distance information together with communication air to

ground and ground to air. The messages are transmitted partly in digital and partly in analogue form with individual address thus providing for a " private channel " according to the RTCA–SC–31 plan.[1]

2. SYSTEM DESCRIPTION[2,3]

TACAN is a Rho–Theta system providing on one r.f. channel bearing information for an unlimited number of aircraft, and distance information for about 100 simultaneous users (Fig. 1). Regarding bearing information TACAN is a phase measuring high-speed rotating beacon, that is distinguished from VOR by an additional " fine system " for more accurate azimuth determination.

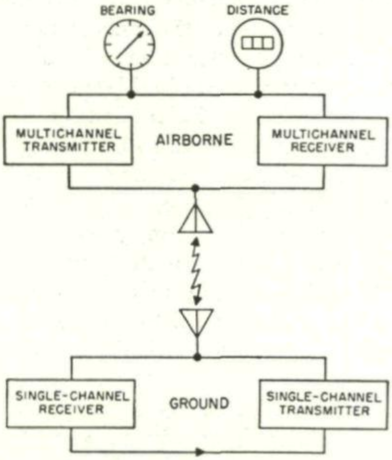

Fig. 1. Radio Elements of TACAN system

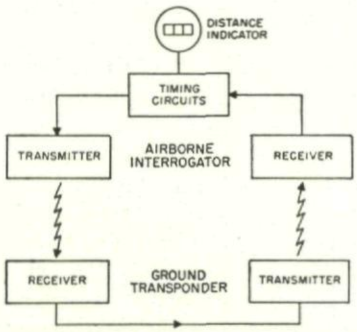

Fig. 2. Principles of navigational distance measurement

The distance is given by measuring the delay between the time a pulse is transmitted from the airborne equipment and the time it is retransmitted from the ground station on a second radio frequency.* A full TACAN channel needs therefore two radio frequencies that are spaced by 63 Mc/s (duplex operation).

* In the airborne equipment compensated for the delay in ground station circuitry.

TACAN is operated in the frequency band 962 Mc/s to 1213 Mc/s with 1 Mc/s channel spacing. One hundred and twenty-six controlled channels are available, which are allocated as follows:

	Channel 1–63	*Channel 64–126*
Ground station		
Transmitter	962–1024 Mc/s	1151–1213 Mc/s
Receiver	1025–1087 Mc/s	1088–1150 Mc/s
Airborne equipment		
Transmitter	1025–1087 Mc/s	1088–1150 Mc/s
Receiver	962–1024 Mc/s	1151–1213 Mc/s

In detail TACAN operates as follows[2]

Distance Measurement

With the airborne equipment set to " transmit " on the preselected r.f. channel 1.5 kW double pulses of about 3.5 μsec duration, 12 μsec spacing and 150 c/s repetition rate are transmitted continuously (searching). The pulse repetition rate is reduced to 27 c/s, if after a search time of 20 sec a continuous distance measurement is achieved.

The switch-over from searching to normal operation tracking takes place when the airborne equipment receives reply pulses from the ground station that are strictly synchronized with the interrogation pulses transmitted. The airborne distance measuring set is so designed that only the reply pulses triggered by the corresponding transmitter can meet this requirement. It should be kept in mind that the ground station can serve up to 100 aircraft simultaneously on one r.f. channel. That means up to 100 reply pulse trains are received in the airborne equipment from which the proper pulse train is to be selected. To assure that, the interrogation pulses are not transmitted with precisely the same pulse pair spacing but with a random jitter imposed on the average spacing of 1/150 sec resp. 1/27 sec. The proper pulse train is selected by a stroboscopic method that refers the measurement of the pulse delay time to the local triggering pulse, thus displaying only one clear and stable or slowly changing pulse train.

Due to the jitter the pulse trains triggered by other aircraft show no compatible periodicity and are therefore rejected by the delay measuring circuit.

For distance measurement purposes the ground station operates with an antenna that has a certain amount of vertical gain directivity but a circular horizontal pattern.

Bearing Measurement (Rotating Beacon Function)

If the ground station antenna used for distance measurement shall also allow operation as a rotating beacon, it is necessary to change the circular horizontal pattern into a directional one rotating around a vertical axis.

The TACAN system employs a " coarse " and a " fine " pattern in order

to increase the bearing accuracy and to reduce the influence ground as irregularities.[2,3,7] The "coarse system" is unambiguous through 360° as VOR. It is produced by a parasitic radiator that converts the original circular pattern into a cardioid (Fig. 3). This parastic radiator, embedded in a plastic cylinder, rotates with 15 periods per second around the antenna and thus the cardioid, thereby producing a 15 c/s amplitude modulation on the TACAN signals. The phase of the received 15 c/s modulation depends on the direction from the ground station to the airborne receiver (rotating phase).

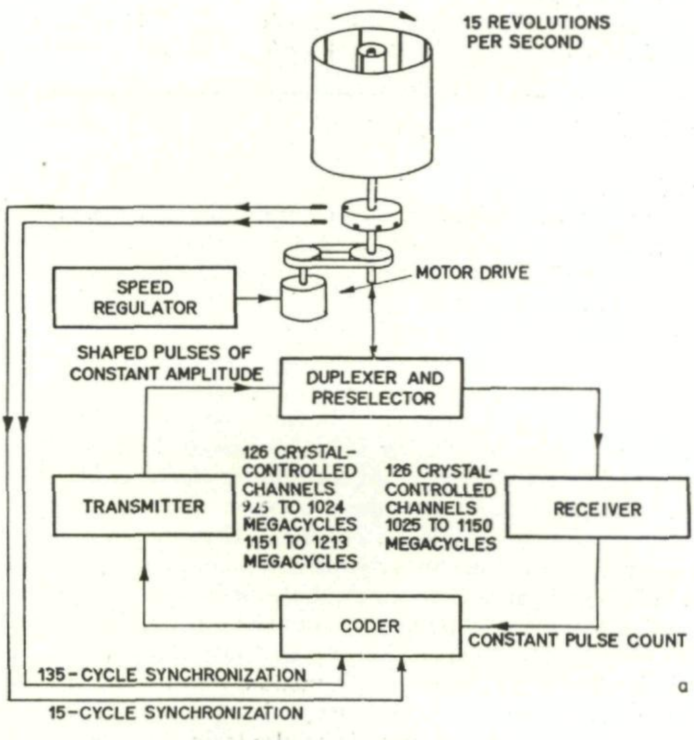

Fig. 3a. Block Diagram.

The "fine system" is nine times ambiguous within 360°. It is obtained from nine director wires arranged around the first reflector within another plastic cylinder forming a fixed assembly with the first one. These nine directors produce nine maxima and minima on the cardioid pattern, or nine minor lobes giving an additional 135 c/s amplitude modulation on the 15 c/s. Three hundred and sixty electrical degrees of the 135 c/s modulation correspond to 40 angular degrees. An error in the electrical phase measurements affects thus the bearing measurement only by one-ninth.

The multiple ambiguity of the "fine system" is automatically dissolved by the TACAN receiver. To achieve this reference signals for the 15 c/s

and the 135 c/s modulation are transmitted from the ground station. For the 15 c/s modulation serves a group of pulse pairs with 30 msec spacing which is emitted when the maximum of the cardioid pattern passes the east direction. After each 40° of rotation a further reference signal, pulse pair groups with 24 μsec spacing, is transmitted in order to determine 135 c/s phase.

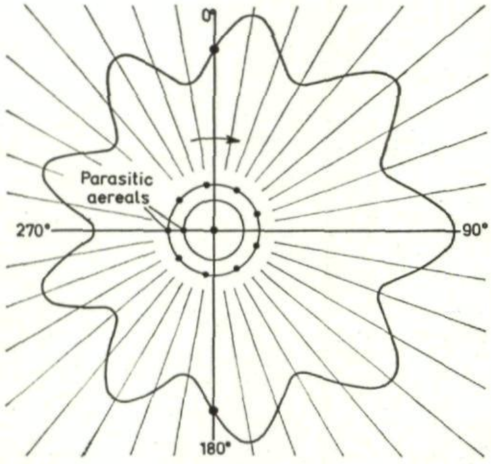

Fig. 3b. Antenna radiation pattern (situation at the moment of radiation of the 15-cycle reference pulse group)

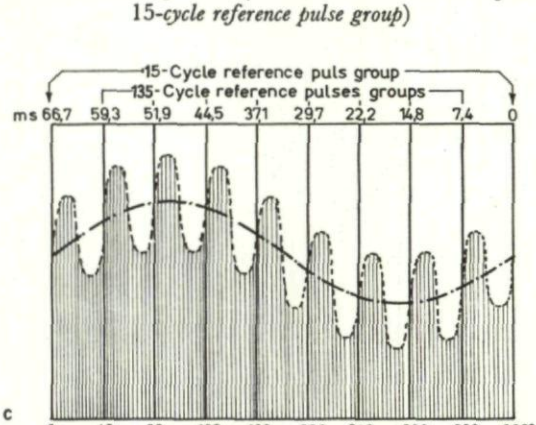

Fig. 3c. Transmitted or received signal as a function of azimuth or time

The operation as a rotating beacon is independent of the distance measuring function. The ground transmitter emits always the same number of about 2700 pulse pairs. In the case when no interrogation pulses are received, all pulses transmitted are of random distribution and provide a constant duty cycle.

For identification purposes each 30 sec a morse signal is transmitted. This does not interfere with the distance and bearing measurement, because

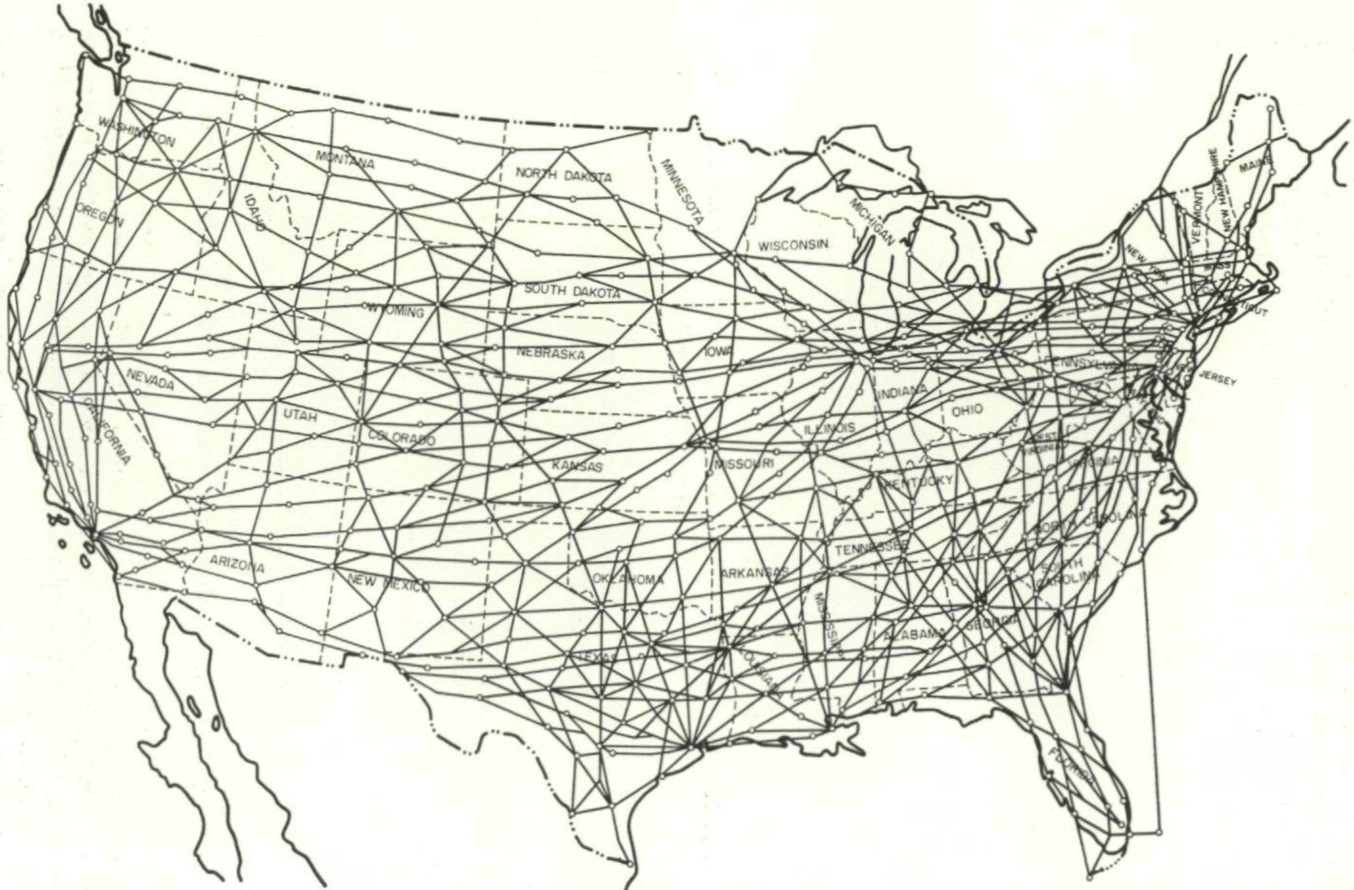

Fig. 4. VORTAC Installation U.S.A. 1965

the airborne equipment has a distance information memory and storage capability which prevents switchover to "searching" during short interruptions of the distance information reception.

3. ACCURACY AND RANGE

3.1. *Accuracy*

Only little information is currently available on the overall system bearing accuracy which is obtained in practical operation. Reference 5 contains figures for five different ground stations:

maximum tolerance	$\pm 0.5°$
97 per cent probability	$\pm 0.4°$
76.4 per cent probability	$\pm 0.3°$

References 6 and 7 state that the maximal tolerance is within $\pm 1.5°$. The error of the ground station is approx. $\pm 0.56°$ (standard deviation) and $\pm 1.11°$ for a 95 per cent probability according to ref. 8. The airborne

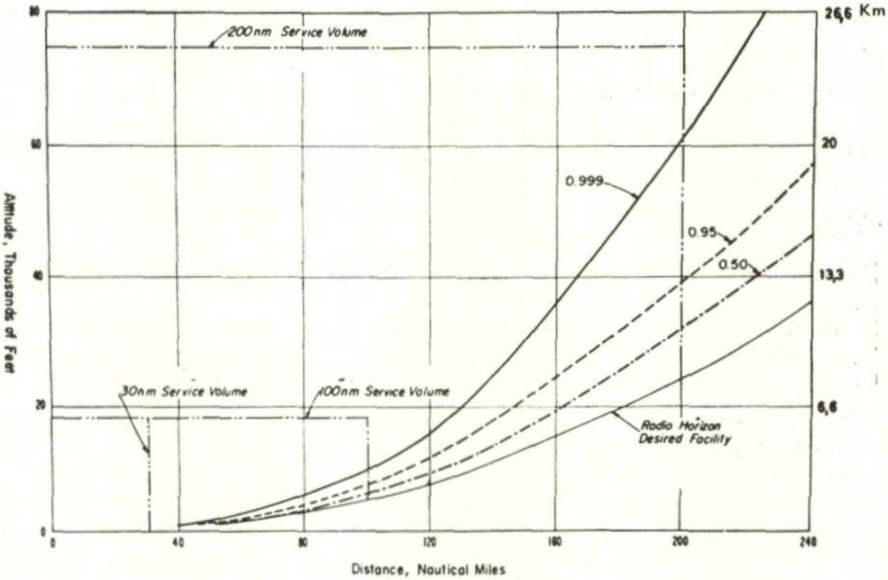

Fig. 5. Probability of Service from a TACAN facility
No interfering facilities

receiver error is assumed to be 0.7° for all practical purposes so that the overall error is approx. $\pm 0{\cdot}9°$ or approx. $\pm 1.8°$ respectively (95 per cent probability) according to statistical rules. The distance measuring accuracy is said to be ± 200 m ± 0.2 per cent of the distance measured. The distance measuring error of the ground station is ± 0.033 n.m. (60 m, standard deviation) or ± 0.07 n.m. (130 m, 95 per cent probability) respectively according to ref. 8. The overall error including the airborne equipment is 0.1 n.m. (185 m or ± 0.24 n.m. respectively; 440 m, 95 per cent probability).

3.2. *Range*[4]

The system figure of merit (ground-to-air path) for modern TACAN equipment (ground station AN/GRN–9, airborne equipment AN/ARN–21) is given by:

transmitter power	67 dBm (5 kW)
antenna feeder loss	6 dB
minimum receiver input power	85 dBm

and from that the system figure of merit 67–6–(–85) = 146 dB. With 146 dB admissible transmission loss and for average gain values of the ground- and the aircraft-antenna the following ranges result for 95 per cent of all the cases:

100 n.m. at 3000 m altitude
200 n.m. at 13,000 m altitude.

if the ground station antenna is 30 m above ground on a smooth terrain (Fig. 5).

The same r.f. channel can only be used by two different ground stations if the distance in between exceeds 500 n.m., because it is intended to use the maximum range of 200 n.m. up to altitudes of 25,000 m.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The radio coordinates supplied by TACAN are fixed radial and circular lines of position continuously available by instrument indication (Fig. 6).

The bearing information (Theta) is referred to magnetic north and indicated as position line from or to the ground station. The distance (Rho) is determined by measuring the time delay of a pulse that is transmitted from the aircraft and returns to it after retransmission from the ground station with a fixed delay.

Because bearing and distance are measured simultaneously and continuously with reference to the same ground station, the system provides also continuous fixes in polar coordinates in the origin of which the ground station is located.

The bearing and distance values can be plotted directly on conventional navigation charts to obtain the geographical position of the aircraft. Since the system is only used for distances up to 200 n.m. the errors due to map distortion remain within tolerable limits.

The connection of automatic pilots, flight logs or plane position displays is possible without intermediate computers. In addition, several models of computers are available which allow automatic flying of courses not leading directly to or from the ground station (off-set course). They are, however, not yet in use for civil aviation purposes.

The most important use of TACAN, as in the case of VOR, is the flying of a course on a radial position line determined by the bearing information supplied from the ground station. It is normally not the TACAN azimuth indicator ID–307 giving the magnetic bearing (qdm) of the ground station that is used for this purpose, but, as with VOR, an instrument indicating the bearing reference to the longitudinal axis of the plane, the radio-magnetic indicator ID–250. Such an instrument combining a compass rose controlled by the master compass, and the bearing indicator controlled by TACAN, allows direct reading of the relative bearing and is for this reason especially

suitable for homing on a radial position line (Fig. 6). Connection of an automatic pilot is possible and used in practice.

For flying a given track (airway) that coincides with the radial position line of a TACAN ground station, the omni-bearing selector ID–249 is particularly suitable. It allows selection of the desired azimuth by means of adjusting a counter. Any deviation of the plane from the so-determined track is indicated by lateral deflection of the vertical pointer on the cross-pointer instrument thus giving the pilot an obvious steering information.

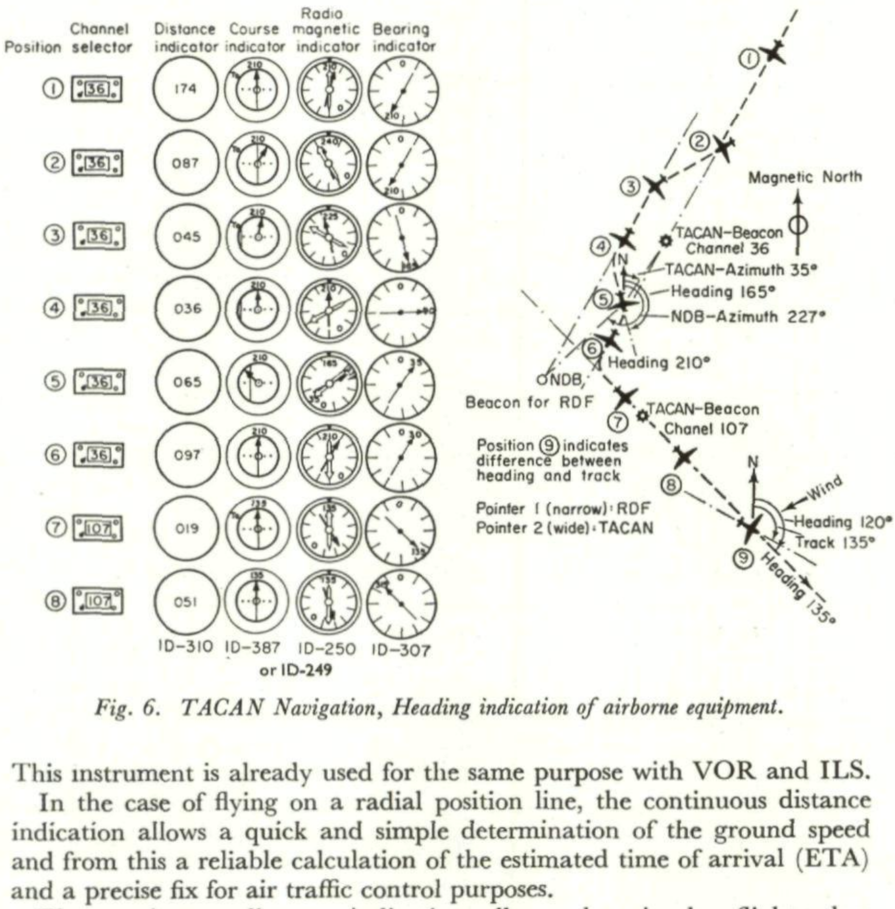

Fig. 6. TACAN Navigation, Heading indication of airborne equipment.

This instrument is already used for the same purpose with VOR and ILS.

In the case of flying on a radial position line, the continuous distance indication allows a quick and simple determination of the ground speed and from this a reliable calculation of the estimated time of arrival (ETA) and a precise fix for air traffic control purposes.

The continuous distance indication allows also circular flights thus providing various navigational means especially for holding and approach procedures.

Control and Operation of the Airborne Equipment

After switching on the equipment, first the r.f. channel selector must be set to the channel of the respective ground station.

Two modes of operation can be selected on the remote control unit: *Position " reception "* (*REC*). Only the receiver is in operation and provides

the bearing information. The transmitter and the distance measuring unit remain switched off. With sufficient power arriving from the ground station it may last 20 sec until "searching" for the bearing information is terminated. Until then the bearing pointer on the azimuth indicator of the radio-magnetic bearing indicator rotates with a speed of 18°/sec, thus showing that a useful bearing information is not yet available. On the omni-bearing selector an alarm indication (flag-alarm) is given during this time.

Position "distance measurement" (T/R). The transmitter and the distance measuring set are switched on, and a double pulse train with 150 c/s repetition rate is radiated. The equipment is "searching" for distance information. The distance indicating counter is blocked for reading by a red cover (flag-alarm). When the stroboscopic measuring unit locks in on the correct pulse train the red cover disappears and the distance from the ground station can be read in nautical miles on the counter. Automatic change-over is provided from the 150 c/s pulses during "searching" to the operational tracking 27 c/s pulse repetition rate.

The instrument indication of bearing and distance is unambiguous. The ambiguity of the bearing "to–from" on the omni-bearing selector has the same properties as with the VOR system and shows if the plane is heading *to* or going *from* the ground station.

5. GROUND AND AIRBORNE EQUIPMENT

5.1. *Ground Station*

AN/GRN–9A, AN/GRN–9B and AN/GRN–9C are the U.S. designations of the TACAN ground equipment which have recently been produced. Older versions, no longer manufactured, have the designations AN/URN–3 and AN/GRN–9.

Besides these a version for ship board installation exists, the AN/SRN–6. The distinction from fixed ground station is a device that keeps the reference direction of the antenna to magnetic north independent of the ship's heading.

There are further transportable TACAN ground stations installed in shelters. They have the designations AN/TRN–6 respectively AN/TRN–6A. A gasoline driven generator providing 30 kVA is part of these installations.

The AN/GRN–9A equipment consists of a transmitter delivering 7.5 kW pulse peak power and a receiver for the interrogating pulses, various measuring and supervisory units and the equipment power supply. The units are assembled within two racks with the dimensions 633 × 905 × 1826 mm. The weights are 530 resp. 580 kg. The power required amounts to 13 kVA. Further separate units of the AN/GRN–9A are the antenna, the antenna control rack that serves for maintaining the antenna speed precisely at its correct value, a monitor, and integral test equipment. Additional facilities are available for remote control and remote supervision of the more important characteristics.

One equipment AN/GRN–9A set comprises only one equipment without standby and thus without automatic change-over. Transmitter and receiver characteristics are continuously supervised by the monitor that disconnects the equipment automatically, if the monitoring tolerances are exceeded in

regard of frequency, transmitter power, receiver sensitivity and distance and bearing measuring accuracy. Disconnection of the equipment by the monitor actuates visual and aural alarms.

The price of an AN/GRN-9A ground equipment amounts approximately to DM 350.000—installation costs not included.

5.2. *Airborne Equipment*

AN/ARN-21 is the U.S. designation of the TACAN airborne equipment recently in series production. A complete set consists of:

	Dimensions				
	Width	*Height (mm)*	*Depth*	*Weight (kg)*	*Volume (l.)*
Transmitter/receiver RT-220 B, Mounting frame MT-298	283	250	524	30.0	37
Remote control unit C 866 or C 1763	146	57	133	0.7	1
Omni-bearing indicator ID-307	83	83	168	1.4	1
Distance indicator ID-310	83	83	181	1.4	1
Phase network CV-279	76	76	124	1	0.7

Additional facilities are:

Radio-magnetic indicator ID-250.

Omni-bearing selector with cross-pointer ID-249 or ID-387.

The antennas used are either of the flush mounted ring slot type or stubs with streamlined cover.

The supply voltages and powers required for the airborne equipment AN/ARN-21 are:

1. 115V a.c., 320 to 1000 c/s, 400 VA
2. 115V a.c., 380 to 420 c/s, 100 VA
3. 28V d.c. 20W

The equipment contains 43 crystals and 80 tubes.

The prices are given in Table 4.3.

For testing and checking the equipment during operation and in the repair shop various special test sets are available.

For the further development of the TACAN airborne equipment it is intended to reduce weight and dimensions, to shorten the " searching " time and to improve the altitude resistance and the cooling of the equipment. This is of the greatest importance for high-speed aircraft. Besides that, the new equipment being developed is planned in such a manner that the

distance measuring unit can be used as a separate equipment for the VORTAC system.

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2.06. VORTAC AND VOR/DMET

K. Bärner

The VORTAC radio navigation system is a combination of the VOR system operating in the v.h.f. band (around 100 Mc/s) and the TACAN system operating in the u.h.f. band (around 1000 Mc/s) (cf. Chapters 2.04 and 2.05). In the VORTAC system, TACAN stations are erected in addition at the site of VORs (cf. Chapter 2.04, Fig. 4). The aerial system of both types of installation are arranged coaxially so that no interfering influences can occur.[1]

Recently proposals have been put forward to supplement existing VOR ground stations, not with a complete TACAN ground equipment, but only with the ground portion of the TACAN system required for distance measurements (transponder) to transmit full Rho–Theta information. This system is referred to as VOR/DMET and is intended for use in civil aviation only.[2,3]

Civil aircraft equipped with VOR receivers and DMET (distance measuring equipment TACAN) can determine the bearing by using either the VORTAC ground station or the VOR/DMET ground station, both of which supply VOR information. Distance measurements are made by the use of the TACAN distance measuring equipment. Military aircraft, however, which are equipped with TACAN airborne equipment only can cooperate with VORTAC or TACAN ground stations. VOR/DMET ground stations, however, supply them only with distance data.

Owing to the introduction of the two ground station combinations described above, civil aircraft need not be equipped with the DMET system which was planned to supplement the VOR system (see page 43).

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2.07. NAVARHO*

T. v. Hauteville

1. INTRODUCTION

Navarho is a long-range Rho–Theta navigation aid operating in the 100 kc/s band. The main operational features are:

(*a*) Full compatibility with short-range systems as VOR, VORTAC, TACAN. This compatibility was obtained by using basically the same principles as with these systems.

(*b*) The ability to display bearing and distance information directly to the pilot.

(*c*) Easy combination of the information obtained with a dead reckoning computer.

(*d*) The ground installation comprises only one station. This simplifies the problem of site selection.

The system was developed in the U.S.A. since 1946–47 by the I.T.T. Laboratories for the USAF, firstly with the name " Navaglobe " (2.03) as a low-frequency rotating beacon supplying only bearing information. This part was demonstrated in 1954 on the occasion of an I.C.A.O. conference.

The distance measuring facilities were developed and tested separately under the name " Facon ". The combination and integration of " Navaglobe " and " Facon " in the same ground station and airborne equipment is known as " Navarho ".

The complete Navarho system was tested extensively from May 1956 to May 1957 with a larger series of flight and ground measurements versus a ground station at Camden, New York. The results of these tests[4] show that especially the accuracy of the bearing values does not yet meet the ICAO requirements.

To improve the accuracy some system modifications were proposed. These versions are dealt with in the sections

2.14. Navarho–H
2.15. Navarho–HH
2.16. Navarho–Rho

These versions, however, are no more genuine Rho–Theta systems but more or less a transition to hyperbolic systems resp. to straightforward distance measuring systems.

2. SYSTEM DESCRIPTION

Navarho supplies distance and bearing information to an unlimited number of simultaneous users. Hence it is a universal and complete Rho–Theta navigation system.[1,2]

* This chapter corresponds to the original version although this system and its variations (cf. Chapters 2.14, 2.15 and 2.16) are less important today.

The bearing information is obtained from the amplitude ratio of three radiation patterns, shifted versus each other by 120° and transmitted consecutively one after the other with the same radio frequency. The ground antenna installation consists of three towers at the corners of an equilateral triangle. The sidelength is about 0.4 wavelength, about 1100 m (Fig. 1). Within 1 sec, first one antenna radiates for 170 msec an omni-directional

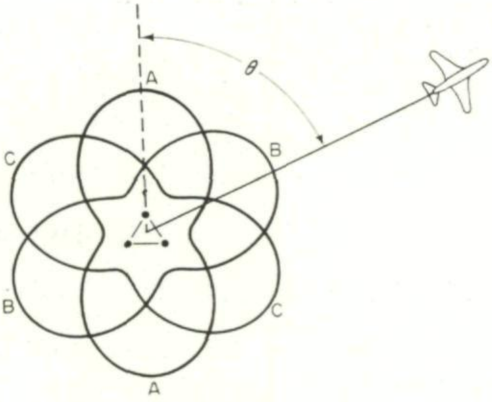

Fig. 1. Antenna diagram of ground station

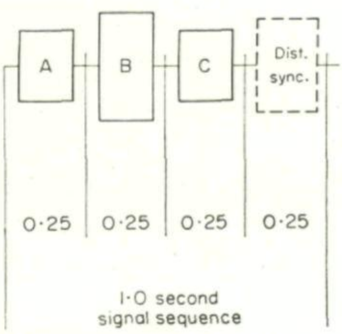

Fig. 2. Signal sequence

pattern, then follows the transmission of the three directional patterns, one after the other, each for 170 msec. The directional pattern is obtained by simultaneous transmission from two antennas. The 170 msec signals are spaced by 80 msec intervals (Fig. 2).

The omni-directional 170 msec signal serves for synchronization of the receiving equipment and for the distance measurement as described below.

To obtain the bearing information the amplitude values received from the three transmit antenna pairs are compared directly by the vector-ratiometer through 5–20 transmission cycles. The result has a 180° ambiguity.

To keep the random variations of the indication within tolerable limits, a sufficient signal-to-noise ratio is required. For a variation of 0.6–0.7° the signal-to-noise ratio must be at least 20 dB within 20 c/s bandwidth. In order to maintain stable amplitude and phase relations between the signals radiated from the three antennas, an automatic control has to be provided on the ground station. The transmitter power stages are associated with the individual antennas. The control and driving power comes from a central control rack.

The distance information is obtained by phase comparison of two signals, one radiated from the ground station, the other one supplied from an airborne frequency standard. If once, e.g. when the aircraft starts, the phase angle between the two signals is correlated to the then known distance, each change of location having a radial component to or from the ground station causes a change of the relative phase between the two signals, provided their frequency stability is sufficient. Thus from the change of the relative phase the change in distance *from* or *to* the ground station can be determined, other than with TACAN, where the absolute distance is measured by a pulse time delay. Navarho only measures how an initial given distance is changed by the motion of the aircraft.

Two different evaluation methods for distance measurement are under test.

2.1. *The Carrier Phase Distance Measuring Method*

With this method the airborne reference standard serves directly for determining the phase variation versus the carrier received from the ground. Because with a 100 kc/s carrier the electrical wavelength is 1.62 n.m., this method is highly ambiguous. This ambiguity can be resolved in various ways, e.g. by the second method of distance measurement described below.

2.2. *Distance Measurement by the Modulation Method*

The ground station transmits after the three consecutive radiation patterns the omni-directional pattern amplitude modulated resp. simultaneously on two RF-carriers spaced 100 c/s or 250 c/s. The aircraft then receives a beat frequency of 100 c/s resp. 250 c/s. Measuring the phase of the 100 c/s resp. 250 c/s signals with reference to the airborne frequency standard gives a high degree of unambiguity: 1620 n.m. for 100 c/s and 648 n.m. for 250 c/s. On the other hand, with this method the influence of the phase measuring error is rather large, for with an electrical wavelength of 1620 n.m. 1° phase measuring error corresponds to a distance measuring error of 4.5 n.m.

Because also the possibility exists that the two carrier frequencies are propagated on different ways, larger measuring errors occur than with the method of 2.1.

Practical experience with the modulation measuring method appears not to be very encouraging. Though the system was originally designed only for the modulation measuring method—the carrier phase method—the carrier phase method is not mentioned in Ref. 2—all accuracy values given in section 3 refer only to the carrier phase method. The modulation method is only mentioned here as a means to dissolve the multiple ambiguity of the carrier phase, but of course only with the accuracy the modulation method

can offer. Mostly, for dissolving the ambiguity of the carrier phase method, the use is recommended of a dead-reckoning computer that continuously evaluates the data obtained and continues the dead-reckoning operation automatically in the case of failing reception.

The real problem, however, of the Navarho method is the difficulty of providing airborne frequency standard of sufficient accuracy. For air navigation purposes a frequency stability of 10^{-9} for at least 12 hours is required (see Chapter 3.5.2, p. 164).

Crystal controlled frequency standards of sufficient stability exist and their airborne use is possible. They require, however, a long heating-up time and must therefore be operated continuously without any interruption. To achieve that a special ground organization would be necessary.

For the future, decisive progress is expected from a molecular standard (atomic clock) that would bring the long-term variations of the crystal to less than 10^{-9} within 12 hours.[6]

For the control of the ground transmitters, atomic clocks appear to be a reasonable solution, because on the ground weight and space occupied are of less importance.

3. ACCURACY AND RANGE[4]

The following results were obtained from testing the only hitherto existing ground station, which operates with approximately 4 kW radiated power.

3.1. *Flight Tests*

Twenty-two test flights were made, the average errors of which are given below. The values are the aggregate error comprising all individual errors introduced by the ground and airborne station, terrain and propagation, instrument reading and by fixing the true position of the aircraft.

	Distance (*n.m.*)		
Errors not exceeded 95 per cent of the time	1100	1500	2000
Distance error (n.m.)	± 9.22	± 16.6	± 35.0
Bearing error degree	± 3.88	± 3.96	± 4.42

3.2. *Ground Test*

3.2.1. *Distance values.*

Distance 1165 n.m. Standard deviation 1.75 n.m.
17 hr observation

Distance 2100 n.m. Standard deviation 0.76 n.m.
15 hr observation

The measurements were made with the carrier phase method.

3.2.2. *Bearing values*. Most values given in the table are based on several hundred individual measurements.

Distance the Observation Was Made (n.m.)	*Standard Bearing Deviation*		
	Day	*Night*	*Dusk*
17	± 0.26°	± 0.32°	± 0.71°
191	± 0.42°	± 1.20°	± 0.52°
1322	± 0.36°	± 1.39°	± 0.58°
2154	± 1.64°	± 1.39°	± 1.10°

The evaluation of the test results obtained shows that it would be desirable to increase the radiated power to 80–100 kW in order to increase the range of 1100 n.m. obtained with 4 kW for 95 per cent of the time, to about 2000 n.m. across land during daytime. The errors estimated for such an increased power are :[4]

Distance error (95 per cent) ± 3–5 n.m.
Bearing error (95 per cent) ± 2°

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The data obtained by Navarho are radial and circular lines of position, the values of which are directly indicated by instruments. The bearing referred to magnetic or geographic north is indicated as line of position to or from the ground station. It is possible to utilize omni-bearing selectors or radio-magnetic indicators as in the case of medium-range systems as VOR (see Chapter 2.04) and TACAN (see Chapter 2.05). The instruments used with the VOR and TACAN airborne equipments could be modified for the alternate indication of Navarho data.

For long-distance navigation, however, direct flying according to the bearing data obtained from the ground station will be far less important than for short-distance operation. It is therefore proposed to feed the position information into a dead-reckoning computer in order to meet the requirements specified for long-distance air navigation systems by the second Air Navigation Conference of the ICAO.[3]

(*a*) Continuous position indication.
(*b*) Bearing to any location within the coverage of the system.
(*c*) Distance from any location within the coverage of the system.

The airborne equipment planned is intended to be remote controlled. The r.f. channels are arranged for 1 kc/s spacing, thus no special operation is required for station selection. Also no additional manipulation is necessary to find the bearing besides the dissolution of the 180° ambiguity.

Only for the distance measurement has the distance indicator to be set to the reference distance at a primary location, e.g. before starting.

When entering from outside into the coverage area of a Navarho station

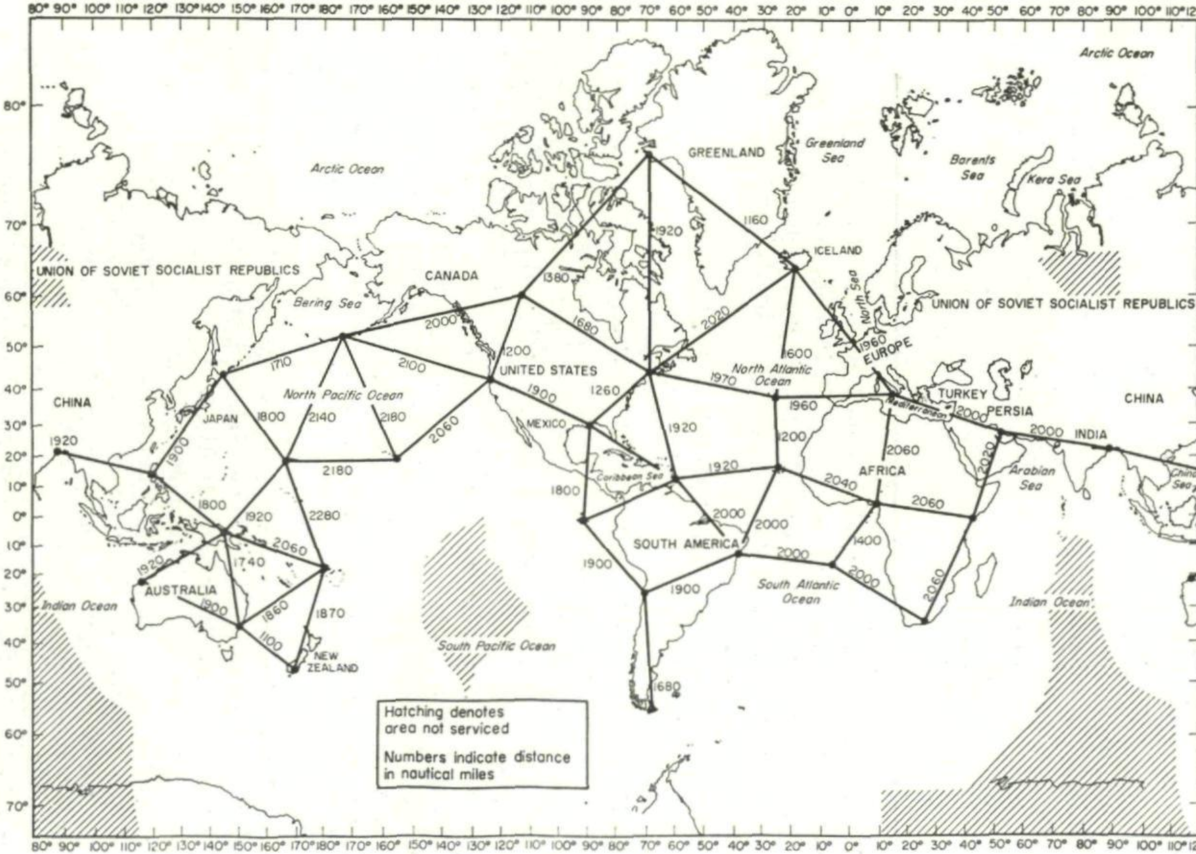

Fig. 3. IT and T—Proposal for Navarho Network

the reference distance has to be obtained by dead reckoning. When passing from the service area of one station into the area of another it is hoped to achieve automatic setting of the distance indication by synchronization of the ground stations.

5. EQUIPMENT

5.1. *Ground Station*

According to information presented by the U.S.A. to the ICAO[4] the following expenditure is to be expected:

Ground station with three 200-m antenna towers and	
for each tower a 15-kW transmitter with standby	\$1.745,000
or for each tower a 100 kW transmitter with standby	\$2.945,000.

The annual cost of operation and maintenance was estimated at \$96,000. That is based on a staff of 12 required for 24 hours' continuous operation.

The terrain requirement for a ground station amounts to something between 150 and 180 ha depending on the operating frequency. The requirements for the characteristics of the site and its surrounding are rather high and normally not easy to meet. First, a marshy terrain with very good ground-conductivity is necessary in order to keep the earth resistance as low as possible. That is, at 100 kc/s, of primary importance for a good radiation efficiency. Secondly, there should be no hills or larger natural or man-made obstacles within a distance of several wavelengths from the station because the bearing is determined by the amplitude ratio of the three radiation diagrams, and any diagram distortion resulting from terrain influences cannot be compensated for. Deviations resulting from such influences can of course be accounted for by individual corrections applied by the user, but that would complicate the evaluation and interpretation of the data obtained.

Based on a useful range of 2200 n.m., 30 ground stations are required for world-wide coverage (Fig. 3).

5.2. *Airborne Equipment*

The following information was given on a simple airborne equipment giving bearing and distance information:[4]

Weight	about 45 kg
Volume	about 70 l.
Power consumption	about 260W
Price	about \$10,000

(based on a series of 500)

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2.08. DECCA

H. Lueg

1. GENERAL INTRODUCTION

The Decca hyperbolic radio navigation system with four ground stations was first used in 1944 and is based on proposals put forward by O'Brien.[1] The four ground stations of a Decca chain are arranged in a star configuration with the Master station located in the centre, and the three Slave stations (purple, red, green) are located at a distance to the Master station of approximately 120–200 km. Similar ideas were put forward by Meint Harms in a German Letters Patent of 1930.[2] A high positional accuracy is obtained at ranges from the Master station of 300–400 km. The effective range of the Decca system is at least 450 km. On the border of the coverage the radial error is less than 8 n.m. (approximately 15 km) at a 95 per cent probability.

The Decca system is based upon the principle of phase comparison. Thus the ground transmitters can be operated without modulation. Only a very narrow receiver pass-band is required ($\pm$ 25 c/s with the Mark 8 receiver, and $\pm$ 10 c/s with the Mark 10 receiver, which is designed as a superhet).

Since no airborne (shipborne) transmitter is required for obtaining a fix, the Decca system can accommodate an unlimited number of users.

Each Decca chain requires four fixed frequencies (with Mark 10 five fixed frequencies). The frequency ranges allocated for this purpose by international agreement, viz. 70.087–70.583 kc/s, 84.105–85.900 kc/s, 112.140–114.533 kc/s, 126.157–128.850 kc/s for normal operation, and 114.943–117.397 kc/s for Mark 10 operation, can accommodate 21 Decca chains. The same frequency group may be used by another chain, if the distance between the two Master stations is approximately 2.300 km, with the frequencies of the Master stations of two different chains being separated by 5 c/s only and the frequency distance of the Slave stations being harmonically related to each other.

The range throughout the coverage is independent of the height, and, thus the system may be used by both shipping and aviation, since a frequency of approximately 100 kc/s is used. Position fixing above the ground stations is also essentially independent of the height (for the special measures taken, see section 4).

Various receiver models are available for airborne or shipborne use respectively. In marine use 2 or 3 fine decometers are read normally to obtain a fix. The values read define hyperbolic lines of position which are overprinted on conventional marine charts. To determine the approximate position for the 1- time, the combined coarse decometer is read. In aviation, the Flight Log is used which displays the position pictorially on charts which are still distorted geographically. However, the degree of distortion

can be reduced in most cases by selection of suitable combinations of hyperbolae. Moreover, a distortionless flight log is being developed.

Further applications of the flight log are discussed in section 2.

Systems using phase comparison techniques become ambiguous when the length of the base line exceeds half the wavelength $\lambda_v/2$ of the comparison signal. When the receiver is moved along the base line by a distance of $\lambda_v/2$, the phase angle of the reference signal is turned by 2π; the decometer indicating the phase angle performs one full revolution. According to the reference frequency, 18, 24 or 30 lanes of a base width of $\lambda_v/2$ form a zone whose width is approximately 10 km on the base line. The position of a lane within a zone is determined by phase comparison of a frequency identical for all zones of a chain (lane identification).

When the Mark 10 receiver is used, the ground stations must transmit an additional frequency, which allows zone identification within five adjacent zones. Moreover, the technical development of the equipment includes a semi-automatic lane identification facility.

Since the total width of five zones is at least 50 km, the residual ambiguity is insignificant from the operational point of view. It should always be possible to resolve this ambiguity by navigational aids other than Decca (dead reckoning, radio direction-finding).

In order to solve the problem of feeding the positional data to the automatic pilot, developments are under way to design a flight log from which appropriate signals can be derived.

The Decca system is also employed in surveying operations both on land and at sea by the use of mobile Decca stations.

One of these mobile stations is the Decca HI-FIX system (high-frequency, high-accuracy fixing). For literature see p. 101.

When aerials which avoid electrostatic charging are used, the Decca system is not easily susceptible to interference because of the long-time constant of the indicating instrument (decometer). Atmospherics usually cause substantially faster phase shifts, and their duration normally is limited to only 0.1 sec, whereas the fast rotation of the decometer pointer takes 0.5 sec.

In order to use the Decca receiver also in conditions of severe interference, such as may occur in the proximity of a thunderstorm, the Decca receiver can be equipped with a device which ensures that the decometer continues to operate on the speed data obtained before the beginning of the interference condition (repeater unit).

A transistorized Mark 10 receiver is being developed.

2. SYSTEM DESCRIPTION[3-7,13,14]

A Decca chain consists of three pairs of transmitter stations of which one—the central Master station—is common to each pair. The Slave stations of a chain are located at the corners of a 120° star configuration. Thus an optimum coverage is obtained with a radius of at least 450 km from the Master station (Fig. 1). The lines connecting the Master station with the Slave stations—the base lines—are normally 120–160 km, and in extreme cases 200 km, in length. The ground stations of a pair of transmitters *A* and *B* (Fig. 2) transmit unmodulated r.f. waves having the frequencies

mf and nf, which are synchronized by their common subharmonic f. The transmissions are received at a field point P, where they are multiplied by

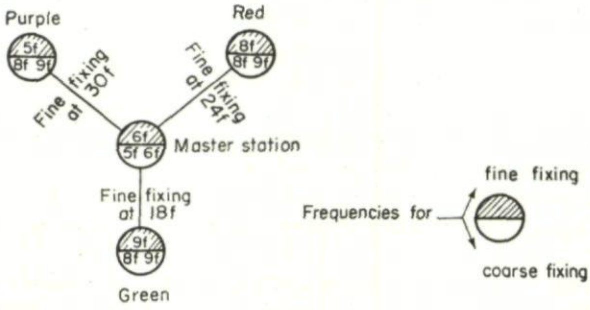

Fig. 1. Layout of the ground stations of a Decca chain with the frequencies assigned for fine and coarse fixing

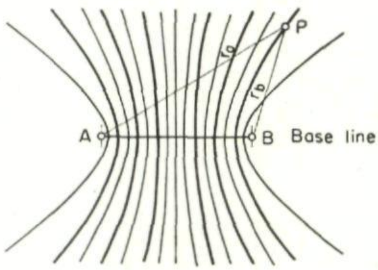

Fig. 2. Hyperbolic pattern

the factors n or m respectively so that two identical frequencies $m \times n \times f$ are produced whose phase difference ϕ then is measured. The phase difference as measured at any point is dependent only upon the difference $r_a - r_b$ under conditions of constant velocity of propagation and, hence, it is constant along a hyperboloid of revolution having the foci A and B.

The following equation applies:

$$\phi = \frac{2\pi}{\lambda n,m}(r_a - r_b)$$

where $\lambda_{n,m}$ is the wavelength of the virtual reference frequency $n \times m \times f$. Assuming the coverage on the surface of the earth of the Decca chain under consideration is regarded as plane, the transmission described above produces a virtual hyperbolic pattern in the receiver after frequency multiplication (Fig. 2). The length of the base line between two hyperbolae of equal phase angle difference is $0.5\lambda_{n,m} = c/2 \times n \times m \times f$.

Frequency multiplication by m or n respectively is required, for otherwise no separation in the receiver would be possible of the electromagnetic waves transmitted by A and B, since the unmodulated synchronized reference frequencies $n \times m \times f$ are transmitted simultaneously.

When the receiving equipment described above is moved over the hyperbolic grid, the phase-angle changes by 360° while the receiving equipment is moved from one hyperbolae to the next. The phase-angle meter (decometer) indicates only the exact line of position within that area between two hyperbolae which is known as lane. This determination of the line of position is called " fine fixing ". When the receiver is moved out of an identified lane, a lane identification is possible by counting the number of lanes traversed. This procedure, however, is applicable only when the position is known immediately before entering the coverage of a Decca chain.

With the ground station layout in Fig. 1 and the transmitted frequencies given in the upper half of the circles representing the transmitters, which are derived synchronously from the common subharmonic f, three virtual hyperbolic patterns can be derived, whose " fine fixing frequencies " are

$18f$ (green hyperbolic grid)
$24f$ (red hyperbolic grid)
$30f$ (purple hyperbolic grid)

The subharmonic f is allocated the range of 14.018–14.316 kc/s. For instance, with $f = 14.166$ kc/s and a velocity of propagation c of 299.250 km/sec, the transmitted frequencies, the reference frequencies and the lane width on the base lines show the following typical values:

	Transmitted Frequencies	
	(*kc/s*)	(*m*)
Master station	85.000	3521
Red Slave station	113.333	2640
Green Slave station	127.500	2347
Purple Slave station	70.833	4225

Lane Width on Base Line (*m*)		*Reference Frequencies*
Red	440.074	340.000
Green	586.765	255.000
Purple	352.059	425.000

The frequency groups issued by Decca are shown in the Table 1 on page 97.

The position is defined by the intersection of two hyperbolae. The positional accuracy is increased with the angle of intersection approaching 90° and decreasing lane width. There is always a sufficient number of hyperbolae intersecting at right-angles available within the coverage of the four transmitters of a chain in any azimuthal direction from the Master station.

Moreover, outside the transmitters new tertiary contours may be derived by adding and subtracting different hyperbolic patterns. Such tertiary contours intersect with the primary hyperbolae largely at right-angles (Fig. 3). This results in optimum combinations for pictorial display purposes (Fig. 4) for the various effective ranges of a Decca chain. The phase angle

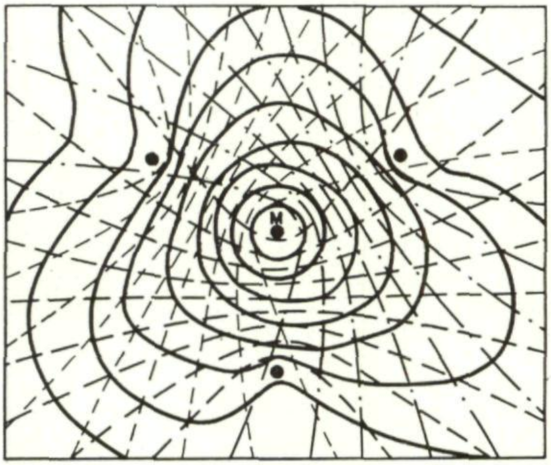

Fig. 3. Primary hyperbolae and tertiary contours of three pairs of transmitters

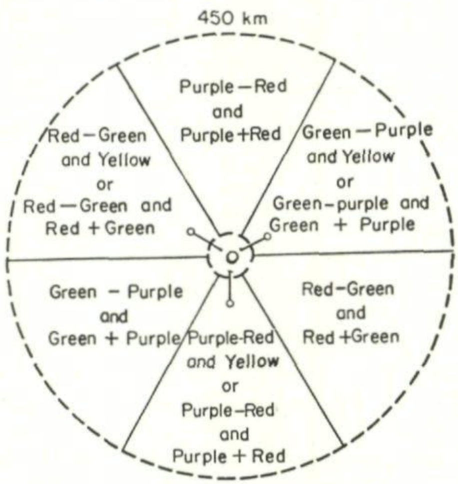

Fig. 4. Combinations for optimum angle of intersection

of each hyperbolic pattern, which is measured separately, can be displayed on three different instruments, the fine fixing decometers, whose outer circular scale is divided into lanes and whose inner circular scale is divided into 1/100 of a lane. The indication is by two separate pointers (see Fig. 5). Since the average lane width on the base line is approximately 500 m, the accuracy of indication is approximately 5 m. The lanes are numbered

according to the assigned multiplication (lane number) and grouped together into zones:

red $24f$, from 0–23,
green $18f$, from 30–47,
purple $30f$, from 50–79.

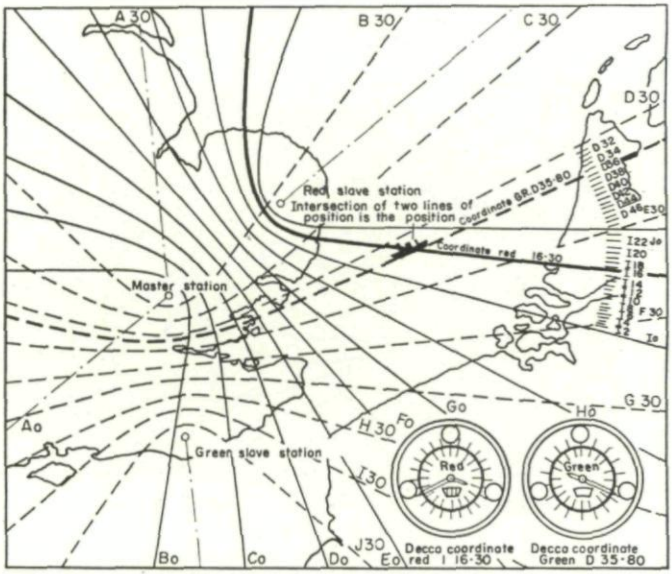

Fig. 5. Lines of position of the red and green hyperbolic patterns of the position of a ship and their display on the respective decometers

The zones of each of the three hyperbolic patterns are denoted by capital letters:
The zone number is equal to:

$$\frac{\text{base line length}}{\text{lane width} \times \text{lane number}} = 2 \times \frac{\text{base line length}}{\text{fundamental frequency } (= c/f)}$$

Lane Identification (Coarse Fixing)

A further facility is provided for lane identification within a zone. Since the range of unambiguity of the zone width is equal to half the wavelength $c/2f$ on the base line with the very-low frequency f of approximately 14 kc/s being allocated, the transmission and, in particular, the reception of these signals becomes difficult because of the low effective height of the receiving aerial. Therefore, each station transmits in addition to its fine fixing signal a lane identification signal by a second transmitter but over the same aerial. The frequency of the lane identification signal differs by the fundamental frequency f from the fine fixing signal. The lane identification signal is transmitted at specified intervals. The Master station cooperates sequentially with each Slave station, thus avoiding confusion. The receiver derives two difference frequencies f from every two frequencies of the stations, $5f$, $6f$, or $8f$, $9f$ respectively. The phase relation of the former is then compared. The zone width on each base line of the above example is 10.562 km. The

ambiguity of the position is reduced to 1/25 by the lane identification process. Thus there will be only 20 ambiguous readings on the base line of 200 km.

This ambiguity is further reduced to 1/5 by another zone identification accomplished in the Mark 10 receiver by means of a reference frequency of $0.2f$. Thus the ambiguity factor is reduced to four within each hyperbolic pattern of a Decca chain.

The transmission cycle provides for the transmission of one lane identification signal for each hyperbolic pattern within each minute. For this purpose the Master station transmits at the beginning of each full minute a signal on the frequency $6f - 60$ c/s, which initiates the red lane identification. This initial signal is transmitted for 1/12 sec. During the following half-second, the Master station transmits simultaneously $5f$ and $6f$ from the same transmitting aerial (see Fig. 1). The red Slave station transmits $8f$ and $9f$, while the transmissions of the purple and green Slave stations are interrupted. The green Slave station, which will be the next station to perform the lane identification, receives the frequencies $5f$ and $6f$ and, after mixing, the frequency $1f$ is used for controlling the phase-locked subharmonic f from which again the commonly transmitted frequencies $8f$ and $9f$ are derived.

The signal on the $6f - 60$ c/s frequency operates a switching circuit on all receivers operating in the coverage of the Decca chain. This switching circuit then switches the receivers for the next half-second so that they derive two reference frequencies f from the four frequencies $8f$, $9f$ and $5f$, $6f$ received. The phase shift of the two reference frequencies indicates the lane identification on a coarse-fixing decometer. In this way approximately 14.5 sec are left until the green lane identification cycle is initiated. During this period the lane identification displayed by the red decometer (lane 0–23) can be checked. After the lane identification period of 0.5 sec all stations change over to the normal condition of fine fixing. At the beginning of the 15th second of each minute, the Master station transmits a signal on the frequencies $6f + 60$ c/s for a period of 1/25 sec. This initiates the green lane identification, which takes 0.5 sec and which is accomplished in the same way as the red lane identification, with the lane identification frequencies given in Fig. 1. At the beginning of the 30th second of each minute, the Master station transmits for a period of 1/12 sec the double frequencies $6f - 60$ c/s and subsequently for 1/25 sec the frequency $6f + 60$ c/s, and thus initiates the 0.5 sec period of the purple identification, which is accomplished as described above. Normal fixing is then accomplished for the rest of the minute, then the new lane identification cycle begins. Figure 5 illustrates the lines of position of the red and green hyperbolic patterns together with the respective decometer indications of a position. The small pointer indicates the line of position within a lane, the large pointer indicates the line of position within a zone, and the letter visible in the small window indicates the zone.

The Decca Receiver[8]

Figure 6a illustrates the block diagram of a receiver during the fine fixing procedure.[3] After amplification and multiplication, the phase angles of $30f$, $18f$ and $24f$ are determined in a four-diode discriminator,

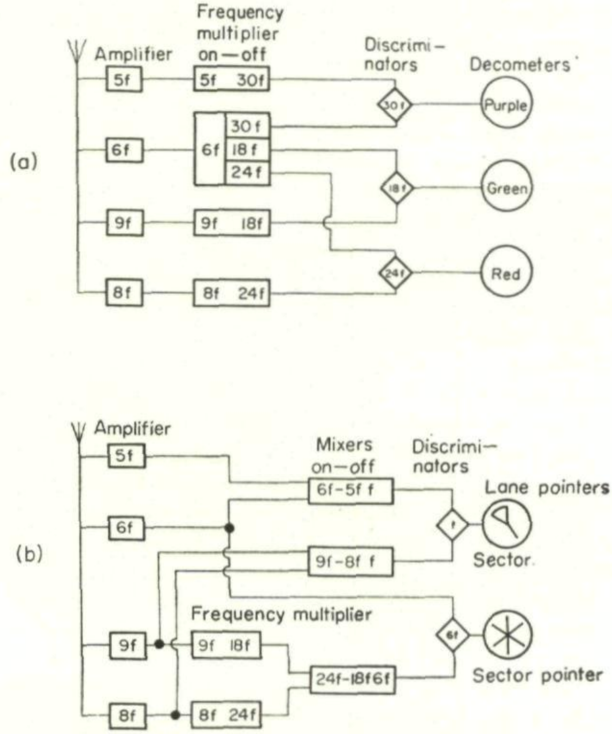

Fig. 6. Block diagram of a Decca receiver
(a) during fine fixing
(b) during coarse fixing

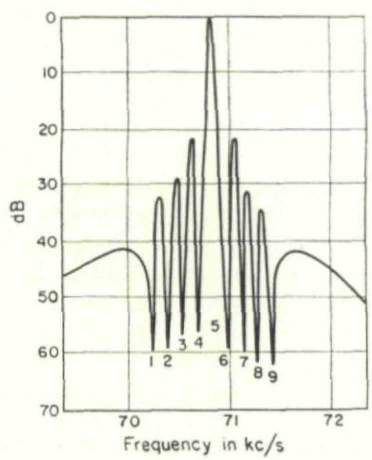

Fig. 7. Frequency response of the input filters of a Decca receiver tuned to frequency 5

whose amplified d.c. outputs are proportional to the sine or cosine respectively of the phase angle measured. These outputs are fed to the field coils of the decometer. In order to prevent variations in the phase angle during reception, the capacitances of the receiving aerial are compensated carefully, manually operated devices are provided for controlling and compensating phase-angle variations in the amplifier circuits and the connected circuits, which may be caused by temperature fluctuations. Each of the four receiver channels is provided with crystal filters, which are tuned to the respective Decca chain by the main switch. The crystal filters of the chains operating on adjacent frequencies act as rejector circuits, whose attenuation of the adjacent frequencies is 50–60 dB (see Fig. 7).

From 1949 onwards Decca chains were provided with a lane identification system. Figure 6b illustrates a block diagram of the necessary receiving equipment. In order to improve the lane identification, the frequency $6f$ is derived from the frequencies $8f$ and $9f$ after frequency multiplication. The frequency $6f$ is compared with the frequency transmitted by the Master station. The phase angle difference of the frequency $6f$ is indicated by a six-armed vernier pointer (indicator) on the lane identification meter so geared that one of the six arms indicates the correct lane. The lane identification meter is provided also with a concentrically-mounted sector indicator which selects the correct arm of the six. In this way the lane identification accuracy is improved by a factor of 6 compared with the comparison of the two derived subharmonics f.

The Decca Flight Log[8]

Various models of flight logs are used, which plot on a chart the track flown. The flight log stylus is controlled by the phase-difference indicated by two decometers or, when tertiary contours are employed, by three decometers. Thus it records intersections of hyperbolic patterns with other hyperbolic patterns, or with tertiary contour patterns respectively. Therefore, the charts used must be distorted in such a manner compared with geographical charts that the families of curves selected intersect at right-angles on the charts. The distortion of the geographical charts thus caused is a disadvantage, whose negative influence can be reduced, however, by selecting suitable combinations of hyperbolae (see Fig. 4). The decometer signals are combined correctly in the flight log computer after the families of curves to be used have been selected. These signals are amplified to such an extent in torque amplifiers that they can be used for driving directly the chart and the stylus, whose motions are at right-angles. The movement of the converter provided after the torque amplifier follows the input phase shift at an accuracy of 1/200 of the width between the fine fixing hyperbolae. Simplicity of manipulation is mandatory in airborne equipment which is to be used by the pilot. Therefore, efforts are made to provide an automatic flight log. The Mark 10 receiver, where the setting of the stylus is acomplished semi-automatically, is a remarkable improvement.

The Mark 10 receiver is described in detail below on page 90.

When appropriate flight log charts are used, continuous operation is possible on longer flights without resetting of the stylus.

High-speed aircraft flying in the vicinity of a thunderstorm might traverse a lane so quickly that it is not counted because of the atmospheric noise.

This avoided by an electro-mechanical flywheel facility (repeater unit) provided in some Decca equipment, for instance with the Mark 8 receiver. The repeater unit is arranged between the receiver and the indicating instrument, where it performs the two following functions, which are highly important for high-speed aircraft:

(1) In conditions of high atmospheric noise, which may simulate rapid changes in phase angle, this unit prevents the indicator from jumping or repeating a lane.

(2) When the strength of the received signal is reduced for a brief period, the receiver is switched off automatically. The flight log then is controlled by the repeater unit. The maximum admissible duration of failure depends upon the quality of reception prior to the failure. When reception was satisfactory prior to failure, the Mark 10 receiver can bridge interruptions of up to 40 sec, and older receiver models of up to 10 sec.

The electro-mechanical control circuit described can be adapted to various speeds and is quite useful in special surveying operations.

The atmospherics occurring in airborne reception of low frequencies are of two kinds:

(*a*) Static charging of the aircraft, which is reduced by suitable discharge facilities on the aircraft.

(*b*) Charged raindrops. For protection against this type of interference, an " anti-static " aerial has been developed, which, as a rule, consists of a vertical rod, whose diameter is approximately equal to the cross-section of a wing, and at whose leading edge a fairing is attached, which protects the receiving element proper from raindrop pulses. Another type of " anti-static aerial " of reduced size is incorporated in the stabilizing fin of the rudder (" suppressed aerial "). The most modern form of the " anti-static aerial " is the " shovel aerial " attached to the lower part of the fuselage.

The Mark 10 *Receiver*[3]

The increased speed and the increased number of aircraft demanded an early solution by the Decca system of the following requirements:

(1) The reliability at night-time of the lane identification on the fringes of the coverage must be improved.

(2) Automation of the lane identification process to relieve the pilot and for correction of the lane identification after severe atmospherics.

(3) Possibility of zone identification within a range of at least 40 km in diameter.

These three requirements are satisfied by the Mark 10 receiver.

For Mark 10 operation, the transmission schedule of the ground stations had to be altered. But in spite of the alteration, earlier receiver models can still perform their functions of position fixing.

For lane identification with Mark 10 the four ground stations transmit

simultaneously a sequence of signals on the frequencies $5f$, $6f$, $8f$ and $9f$ synchronized with the subharmonic f. In order to render possible a zone identification within five zones a signal on the frequency $8.2f$ is also transmitted.

While one of the four ground stations transmits these five lane identification frequencies simultaneously from the same aerial, the transmitters of the other three stations are switched off. The Mark 10 receiver, which has been prepared by previous signals (for instance, for green lane identification), receives from the green Slave station all the above five frequencies according to a fixed time schedule. It derives the common subharmonic f from $5f$,

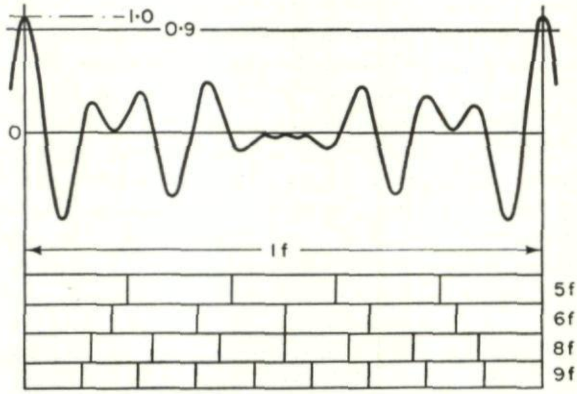

Fig. 8. Superposition of the frequencies $5f$, $6f$, $8f$ *and* $9f$ *in Mark* 10 *operation*

$6f$, $8f$ and $9f$. A continuous oscillator is phase-locked by this subharmonic. Furthermore, the frequency $0.2f$ is derived by mixing, which synchronizes in phase the green zone identification oscillator. Subsequently, the transmission from the Master station is received and the Mark X oscillators of the frequencies f and $0.2f$ are also phase-locked. Thus only the " stored " phase angle of the f or $0.2f$ frequency respectively of the oscillators of the green Slave station and of the Master station can be compared. In this way the lane identification or zone identification within five zones respectively is obtained. Identifications with the other hyperbolic patterns are performed in a similar manner.

The advantage of the Mark 10 lane identification system will be realized immediately from the following discussion: The superposition in phase of the four fixed frequencies $5f$, $6f$, $8f$ and $9f$ result after reduction in the receiver to equal level in the contour shown on Fig. 8. There the frequency f forms a pulse-type peak.

With the normal lane identification system, providing no appreciable phase distortion occurs along the transmission paths, accurate lane identification is obtained. This condition exists within the normal coverage of a Decca chain in daytime, when differential sky wave effects on the individual signals are small, but it may not hold when the amplitude of the

ky wave component exceeds 28 per cent of the ground wave value.[16] In practice this means that, over land, consistently accurate lane identification may extend even during twilight and night to ranges of some 260 km.*

In Mark 10 operation, where the comparison frequency f is formed by four frequencies, i.e. by twice the information content, the amplitude of the sky wave may be up to 44 per cent of the ground wave amplitude in the case of most unfavourable sky wave phase relation, before incorrect lane identification occurs. There liable range of lane identification at night thus is increased to a distance of 450 km from the Master station. In Mark 10 lane identification by phase comparison of the f signals, only that portion exceeding the top line of Fig. 8 is used. The upper limit corresponds to 90 per cent of the total amplitude with superposition in phase. A calculation shows that the 90 per cent limit (amplitude 0.9) is only exceeded by summation of random phase shifts of the four frequencies $5f$, $6f$, $8f$ and $9f$ having an amplitude of 0.25, when to each of the four frequencies a sky wave is added, whose amplitude does not exceed 44 per cent of that of the ground wave, even if the phase angle is most unfavourable.

Hence, when the superposition of the four lane identification frequencies $5f$, $6f$, $8f$ and $9f$, which are reduced to a common amplitude, does not exceed the 90 per cent limit, the lane identification is always correct. So when a lane identification can be performed with the Mark 10 receiver at night-time, the lane identification is known to be correct. When the lane identification is accomplished with only two pairs of frequencies, $5f$ and $6f$, or $8f$ and $9f$ respectively, always the instantaneous phase angle is measured independent of the magnitude of the sky wave influence. It is *not* known at night, whether or not the lane identification is correct. The time interval between the peak pulses above 90 per cent of the frequency f, which is stored after each Mark 10 lane identification, is used for the semi-automatic lane identification system. Zone identification and lane identification is accomplished once per minute for all three families of hyperbolae.

The Reasons for the Frequency Range Chosen, Problems of Propagation

The low frequency band around 100 kc/s is most suitable for the Decca system. With *lower* frequencies, the aerial system of the ground stations would necessitate larger investments to obtain the same transmission power. The effective height of the aerial would be decreased with respect to the airborne receiver. These factors together with the higher noise level of the lower frequencies would necessitate a substantial increase in the transmitter power. The use of *higher* frequencies results in attenuation of the ground wave, but on no account a reduction of the sky wave influence. Thus fading would occur at night at increasingly shorter intervals thereby reducing the range. Furthermore, contrary to very high frequencies, the low frequencies descend to the bottom of deep valleys.[9] This is of importance when the Decca system is used in helicopter operations. Extensive studies of the conditions of propagation and phase variations in the 70–130 kc/s band are discussed in refs. 10 and 11.

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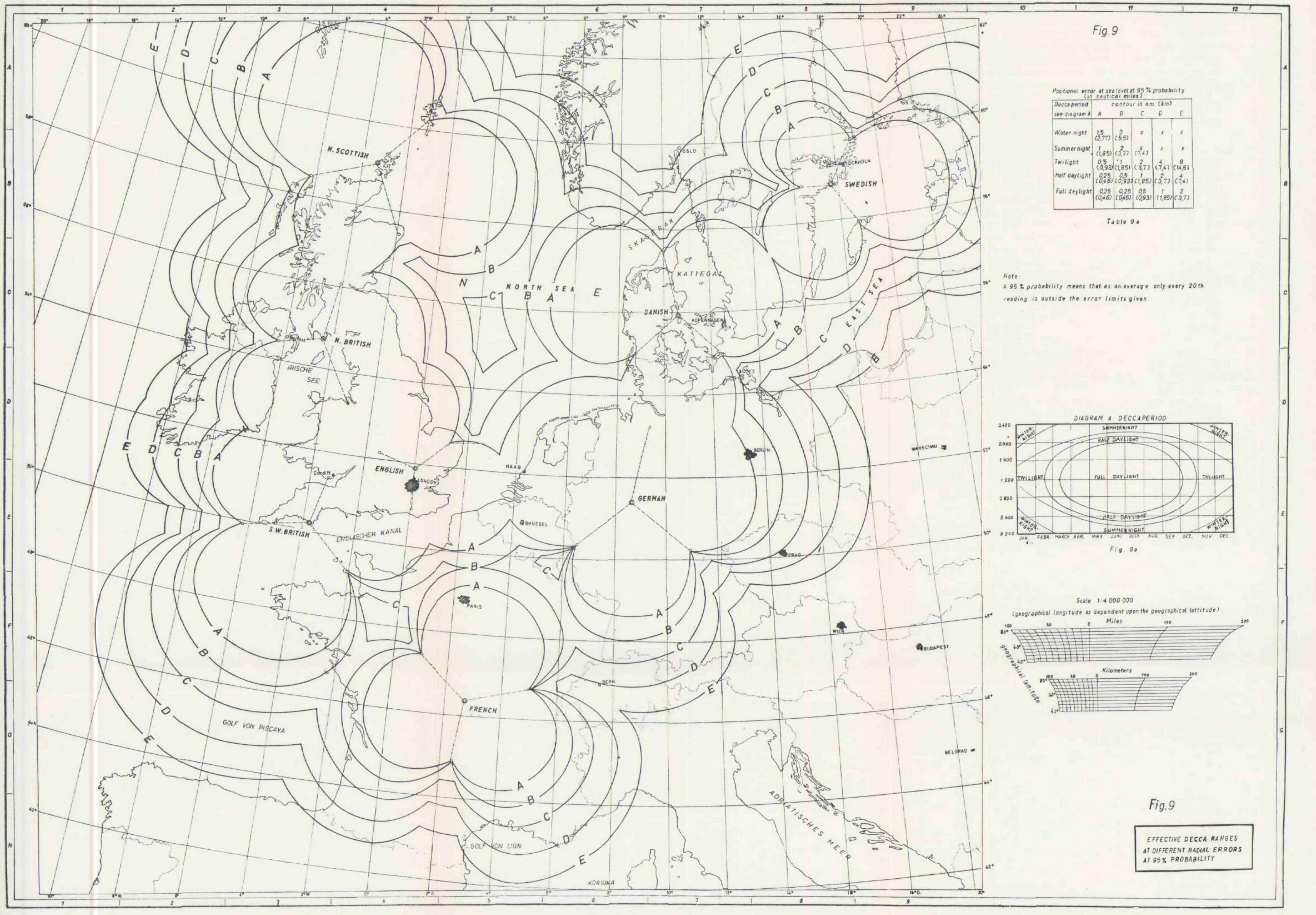
* If propagation is primarily over sea, longer lane identification ranges are obtained.



Positional error at sea level at 95 % probability (in nautical miles)

Decca period see diagram A	contour in n.m. (km) A	B	C	D	E
Winter night	1,5 (2,77)	3 (5,5)	x	x	x
Summer night	1 (1,85)	2 (3,7)	4 (7,4)	x	x
Twilight	0,5 (0,93)	1 (1,85)	2 (3,7)	4 (7,4)	8 (14,8)
Half daylight	0,25 (0,46)	0,5 (0,93)	1 (1,85)	2 (3,7)	4 (7,4)
Full daylight	0,25 (0,46)	0,25 (0,46)	0,5 (0,93)	1 (1,85)	2 (3,7)

Table 9a

Fig. 9. Effective Decca ranges at different radian errors at 95 per cent probability

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3. ACCURACY AND RANGE

The effective range can be stated only when the maximum radius of the 95 per cent circle of uncertainty is given. Assuming the standard deviation on all base lines be $\pm$ 10 m, the range contours at radial errors of different magnitude are calculated as in Section 5, accuracy and range, and illustrated in Fig. 8. The assumption of a base line standard deviation of $\pm$ 10 m is applicable only under favourable conditions. If the waves are propagated over broken terrains, the standard deviation occasionally may be increased by a factor of 4. At night and during the winter season, the propagation conditions are subject to greater variations because of the increased influence of the sky wave. The values of the figure mentioned above remain correct only when the 95 per cent radial error is multiplied by the diurnal and seasonal factors given in the figure [10–14].

The calculated contour corresponds to the real conditions within the triangle formed by the Slave stations. At greater ranges, the reduced field strength, the phase deviation due to increased sky wave influence and, most of all, the correlation beginning at that point (which may assume a value of $\frac{2}{3}$) must be taken into account.

These three influences increase the mean radial error or reduce the area of a given effective range and result in the contours (shown in Fig. 9) in which the mean radial error of *A*, *B*, *C*, *D* and *E* (see Table 9a) is not exceeded in 95 per cent of all cases.

The contours were calculated by the Decca Navigator Co. The calculations are based on a standard deviation of $\pm$ 10 m on the baseline. The effective ranges are greater over sea than over land.

Besides accidental errors there are systematic errors, which, if caused by instrumental errors that can be calibrated, are of such a magnitude that they need be taken into account only in special surveying operations.

The instrumental errors of the Master and Slave station comprise deviations of $\pm$ 0.02 lanes of the individual hyperbolae from their nominal values. Such errors are due to variations within the equipment.

The hyperbolae of the Decca chains are calculated for an average and constant velocity of propagation. Hence, deviations from such velocity cause systematic errors. The velocity of propagation is also influenced by the climate and the humidity of the soil. Systematic errors become important close to the coast. The deviations occurring (coast refraction) are indicated on data sheets used in marine navigation.

Detailed studies of the daily and diurnal variations have been made since 1952 by W. Feyer at several observation stations within the coverage of the German Decca chain.[12] These investigations showed that the coarse long-term variations during winter are related statistically to long-term variations in the air temperature. Therefore, it seems possible to apply this correlation caused by the variation in the complex ground conductivity to a systematic correction of radio navigation systems operating in the 100 kc/s region.

Since the areas of equal phase-angle difference are hyperboloids, systematic errors occur at greater altitudes, whose magnitude is particularly great in the proximity of the respective ground stations. This error can be reduced greatly, however, if when flying over a ground station, only such

hyperbolae are used which do not originate from the particular transmitter or the nearest transmitter. This is always possible with the Slave stations and also with the Master station.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

Aviation

Different receiver models are available for use in helicopters, jet aircraft and slow civil aircraft. Since the values of the primary radio coordinates indicated by the decometers require plotting on a chart, they cannot be used by the pilot for navigational purposes. Therefore, the flight log was developed for aircraft use, which is generally provided with Decca airborne equipment.

The flight log indicates very accurately and continuously the position within the coverage of a Decca chain (see Fig. 9) and records the track flown.

The Decca system with flight log allows deviation from a rigid airway system. New airways or the re-location of airways requires no alteration of the aids to navigation; only the flight log charts of the region concerned must be altered. The following advantages are claimed for the use of flight logs:

En route navigation. Better track-keeping on airways, reliable circumnavigation of prohibited areas and danger areas without additional radio navigation facilities, early recognition of wind drift, simple calculation of the ground speed by the automatic entry of time marks on the chart, greater reliability in determining the estimated time of arrival (ETA). The flight log allows changing from one route to another at any time, if the charts were prepared accordingly. Thus the system is highly adaptable to different conditions of operation.

In the terminal control area the accurate position display is likewise advantageous. Holding patterns may be carried out at any point of the coverage, from which the aircraft can perform a timed approach on approachways length is determined by the aircraft speed and the wind direction. Thus the landing rate can be increased. Maintaining discreet approachways, which are entered on the flight charts, requires no R/T traffic. The problems of identification in the case of radar surveillance is simplified in that the pilot always can give his exact position when requested by the control tower. Thus no special identification manoeuvres are necessary.

The flight log can be operated easily. After the preparations prior to flight (joining and inserting the required charts, fixing the Decca coordinates for setting the flight log stylus when a chart change is to be performed) the stylus is placed on the exact position on the chart prior to take-off. When a chart change is required (*en route*) the stylus must be re-set. Simplifications achieved on the Mark 10 receiver or by selecting the proper charts has been discussed above. It is recommended that the correct position displayed be checked by reference to the decometer readings; if necessary, the stylus should be re-set. Such checks are especially important prior to entry into the terminal control area and prior to the commencement of holding and approach procedures. A combination of letters and numerals has been fixed for each chart, which must be adjusted on the control equipment on take-off or when the chart was changed.

The flight log charts contain all data necessary for the navigation of the aircraft. The flight log charts used normally provide the following information:

(*a*) the airway system;
(*b*) distance in nautical miles from the aerodrome of departure to the terminal airport;
(*c*) arrows indicating north at several points of severely distorted flight log charts;
(*d*) topographic features as necessary from *en route* navigation;
(*e*) information on air traffic control facilities;
(*f*) the lines of two hyperbolic lattices by means of which correct setting of the stylus can be checked.

Reduced signal strength conditions are indicated intermittently by a yellow alarm lamp provided on the flight log.

During 1960 the Decca Navigator Co. developed an "Omnitrac Airborne Computer" for converting continuously the Decca-hyperbola-coordinates into rectangular coordinates in 600 msec. The computer accomplishes all operations which are necessary for immediate track guidance and even for connection to the automatic pilot.

Shipping

The data measured are interpreted on board ships by plotting on Mercator charts which are overprinted with the calculated hyperbolic patterns. Since the shipborne receiver is of the crystal-controlled type and contains the crystals of all the chain frequencies, manipulation is reduced to selecting the required chain. A track plotter has been developed for navigation on shipping lanes; the course made good is plotted on slightly distorted charts.

5. GROUND STATIONS AND AIRBORNE (SHIPBORNE) EQUIPMENT

Ground Stations

Each Master and Slave station comprises:

Transmitting equipment. Three oscillator stages, one fine fixing and one lane identification transmitter output stage each, one additional lane identification transmitter output stage for the purple Slave station, standby transmitter, automatic change-over equipment and incorporated monitoring equipment. Power of each output stage: 2.4 kW, connected load 15 kVA, the average FOB price of a transmitter installation is DM 282,000, and DM 400,000 for Mark 10 Decca.

The aerial equipment of the Master station consists of a self-radiating aerial tower of 100 m in height and an additional standby T-aerial which is 180 m in length and supported on three towers of 48 m in height. The counterpoise of the main aerial tower consists of 120 zinc-plated iron bands each 100 m in length. For the three Slave stations a mobile standby aerial system is provided similar to the standby system of the Master station.

The price of the aerial equipment ranges from 40,000 to 100,000 DM, according to the type required as determined by the local conditions.

At least one monitoring station is required for each chain. The monitoring station is equipped with receiving equipment, indicating and recording instruments which cost 35000 DM.

A set of service valves of a ground station costs 5000 DM. Cubage of each ground station: approximately 1300 m^3. The erection and placing into service requires approximately 500 hr, the commissioning requires approximately 160 hr. The current operating costs of each ground station are:

costs of valves per annum	6200 DM
megawatt-hours per annum	120 for Master 100 for Slaves

Equipment-maintenance costs per annum: approx. 10000 DM.

According to the present technical status, the phase- and frequency-locked transmission is accomplished automatically to the extent of 60 per cent; 40 per cent of manual operation is still required. Three radio mechanics are required for each Slave station for maintenance and trouble shooting.

Since the Master station controls the transmissions of all the Slave stations, five radio mechanics are required for full-day operation of the Master station.

Airborne Equipment

The various requirements of aviation are satisfied by the modern Decca receivers Mark 7, Mark 8, Mark 9 and Mark 10.

All of the above receiver models have in common:

RECEIVING UNIT (straight amplifier circuits, only Mark 10 with superhet-circuit, crystal filters). Decometer group (Mark 8 with three fine fixing decometers and one lane identification meter; Mark 7 lane identification is incorporated on each of the three fine pattern decometers; on Mark 10 lane identification and zone identification are on the fine pattern decometers. The Mark 9 receiver does not normally use decometers, since the output is fed directly to the flight log).

FLIGHT LOG, remote control unit (with pilot lamps) by which all switching on and off operations and the chain selection are performed; the unit is located near the navigator or in the cockpit.

POWER UNIT, and AERIAL with aerial booster.

The FOB price in Great Britain, dimensions, power requirements and special characteristics of the receivers are given in Table 1.

All flight log models have in common: the control, box (chart selection, stylus setting, switching on and off), the mechanical and electrical components of the torque amplifier, the display head and the chart holder. Chart capacity, visible chart area, weight, size, FOB price in Great Britain, power requirements and special characteristics are given in Table 2.

Connections are provided on all receivers for decometer repeaters and flight log repeaters.

The average costs per annum of valves refer to 1000 hr of service and amount to approximately DM 2000. The maintenance costs for the same period amount to approximately DM 3000.

Shipborne Equipment

The Mark 5 receiver has been developed for shipborne operation. It consists of a receiver unit (straight amplifier circuits, with quartz filters, with change-over facility to nine chains), one display unit (three fine decometers, one lane identification decometer with six-armed vernier pointer and zone sector indicator), vertical wire aerial, and, if required, with rotary converter supplying 220–230V, 50 c/s and 250W; weight 42 kg. The weight of the receiver and display units is 45 kg. A decometer repeater for marine receivers is available (FOB price DM 3000, weight 14.5 kg). The Mark 5 receiver is provided with connections for the track plotter which costs (FOB) DM 11,800 and weighs 61 kg.

The Mark 5 receiver costs DM 22,500 (FOB).

Table 1. Frequency-Groups of Decca-chains in operation to Dec. 1960

Chain No.	*Chain*	*Master (kHz)*	*Red (kHz)*	*Green (kHz)*	*Purple (kHz)*
1(*b*)*	S.W. British	84.280	112.373	126.420	70.233
1(*c*)	South Persian Gulf	84.285	112.380	126.4275	70.2375
2(*b*)*	E. Newfoundland	84.461	112.615	126.691	70.384
3(*b*)*	N.W. British	84.645	112.860	126.967	70.537
4(*b*)	Swedish	84.825	113.100	127.238	70.688
5(*b*)*	English	85.000	113.333	127.500	70.833
5(*c*)	North Persian Gulf	85.005	113.340	127.5075	70.8375
6(*b*)	W. Newfoundland	85.180	113.573	—	70.983
6(*c*)	N. Scottish	85.185	113.580	127.777	70.987
7(*b*)*	Danish	85.365	113.820	128.047	71.137
7(*c*)	Nova Scotia	85.370	113.827	128.055	71.142
8(*b*)*	French	85.545	114.060	128.317	71.287
9(*b*)	German	85.720	114.293	128.580	71.433
9(*c*)	Quebec	85.725	114.300	128.587	71.437

* Chain is installated for Mark 10.

Table 2. Prices, Measures and special characteristics

Receiving Equipment	*Component*	*FOB Price in the U.K. (in DM)*	*Weight (kg)*	*Overall Dimensions (cm) (width × depth × height)*	*Power Consumption*	*Special Characteristics*
Mark 7	Aerial booster 308	494	0.5	9.7 × 15.0 × 6.4	24V 11.5A	Electronic flywheel facility for preventing lane loss
	Receiver 276	11,321	15.8	40.0 × 39.7 × 29.7		
	Three Decometers 273	3572	1.4	11.3 × 7.6ϕ		
	Control box 278	635	0.5	14.1 × 5.6 × 5.6ϕ		
	Power supply 277	1950	10.5	14.5 × 15.0 × 19.8		
	Total	17,972				
Mark 8	Aerial booster 308	494	0.5	9.7 × 15.0 × 6.4	24V 12A	Can be provided with repeater unit
	Receiver 351	11,057	16.0	39.0 × 40.0 × 20.0		
	Decometers: Normally one red, one green, one purple 274/5 lane identification	2428 593	fine 0.55 coarse 0.73	9.5 × 7.3ϕ 14.0 × 7.3ϕ		
	Control box 356	217	0.5	14.5 × 6.3 × 7.1		
	Power supply 277 Electro-mechanical flywheel unit (repeater unit)	1950 9929	10.35	14.6 × 39.69 × 19.68		
	Total *with* Repeater unit *without* Repeater unit	26,668 16,739				

Table 2 (continued)

Receiving Equipment	*Component*	*FOB Price in the U.K. (in DM)*	*Weight (kg)*	*Overall Dimensions (cm) (width × depth × height)*	*Power Consumption*	*Special Characteristics*
	Aerial booster 308	494	0.5	9.7 × 15.0 × 6.4		
	Receiver 744	5957	5.6	15.2 × 20.3 × 31.8		
	Control box 751	300	2.2	31.8 × 22.5 × 3.5	24V	Requires little space its weight is low, range is limited
Mark 9	Computer and power pack for receiver and computer 395	4465	6.12	15.2 × 20.3 × 31.75	11A	
	Display head 720	3278	2.15	43.2 × 17.9 × 3.6		
	Total	14,494				
	Aerial booster 308	494	0.5	9.7 × 15.0 × 6.4		Automatic lane identification, automatic lane adjustment, zone identification within five zones. Increased range
	Receiver 800	18,213		60.3 × 39.4 × 19.7		
Mark 10	Decometers	3525				
	Control box 801	1293		14.4 × 9.5 × 7.5		
	Power Supply 859	2056	9.98	20.3 × 29.7 × 19.7		
	Total	25,581				

Table 3. Flight Log Equipment

Equipment/Model	*Size of Visible Chart Area (cm × cm)*	*No. of Chart per Roll*	*Weight (kg)*	*Overall Dimension width × depth × height (cm × cm × cm)*	*FOB Price (DM)*	*Special Characteristics*
Display head 331	25 × 20	until 12	0.45	30.0 × 14.0 × 14.3	3478	Suitable for computers 750, 722
Display head 720	12.7 × 38				3278.25	Suitable for computer 395
Computer 750			7.4	12.6 × 20.0 × 40.6	8935.75	Fed from receiver
Computer 722			7.4	12.6 × 20.0 × 40.6	8935.75	Fed from receiver
Computer 395			6.12	15.2 × 20.3 × 31.7	8935.75	Fed from receiver
Control box 332			1.2	13.7 × 14.6 × 6.4	893	Scale selection, selection of the hyperbolic patterns, remote control

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2.09. DECTRA

DECca Tracking and RAnging

H. Lueg

1. GENERAL INTRODUCTION

The DECTRA system is a hyperbolic long-range radio navigation aid for continuous position fixing between two base lines which may be disposed at 3000–4000 km apart, if signals of corresponding strength are transmitted from the ground station.[1] The originally planned coverage is not limited to the lane extending from one base line to another, but extends to the left and to the right up to approximately half the distance between the two base lines. This extended range is useful for navigational purposes only if the take-off and terminal points are located within it, or if one enters the DECTRA coverage from outside, with the position being known for some other navigational aids.

The DECTRA system has been evolved from the Decca system. The airborne equipment with Flight Log may be used both for Decca and DECTRA. Moreover, two of the four Decca ground stations may be used also for DECTRA. A first experimental chain with only three ground stations was placed into service in May 1957 between Scotland (Prestwick) and Newfoundland (Gander) (Fig. 1b). The trials carried out so far by the U.K. Ministry of Supply and various airline companies have shown that the DECTRA system satisfies the requirements of a long-range radio navigation aid, especially with regards accuracy.

The application in shipping of the DECTRA system is being tested at present. Sufficient data allowing a final assessment of its suitability for marine use are not yet available.

The DECTRA system can accommodate an unlimited number of users, who can establish fixes independently of each other. Attempts are made to automate the flight by feeding the navigational information to the automatic pilot. The current developments of a semi-automatic setting of the Decca Flight Log stylus are equally important for DECTRA.

2. SYSTEM DESCRIPTION

The DECTRA Ground Stations with the Assigned Hyperbolic Patterns

Figure 1 illustrates the transmitting stations A, B, C and D required for DECTRA radio navigation as originally planned. The stations A, B and C, D are disposed at approximately 150–200 km apart (base line length). The two stations on a base line also may be the ground stations of a Decca chain. In this case, the DECTRA Master transmitter A is located on the site of the purple Slave station of the Decca chain, and the DECTRA Master transmitter B is located on the site of the Decca Master station.

The hyperbolae produced by the base line transmitters A, B and C, D are known as a tracking pattern of hyperbolic lines with the ranging pattern

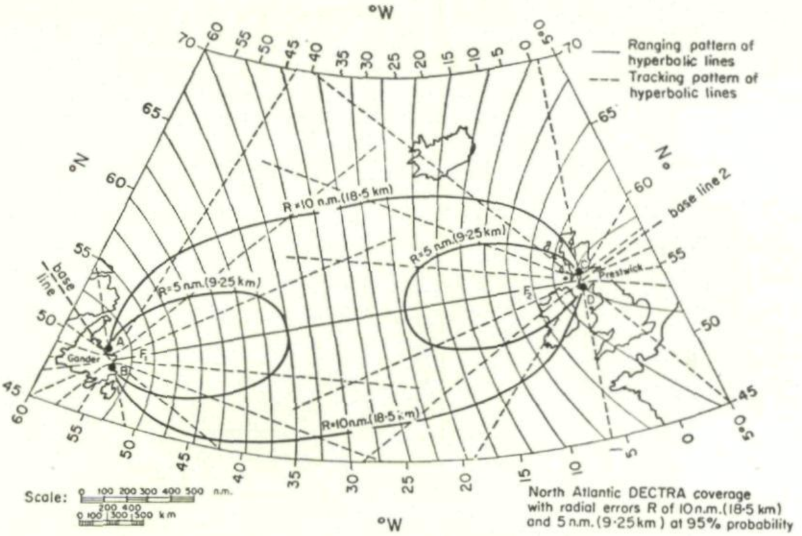

Fig. 1(a). Operational trackkeeping accuracy, worst direction, n. miles, standard deviation of the present 3-station North Atlantic-DECTRA chain. (Measurements of the A.A.E.E.—Aeroplane and Armament Experimental Establishment—of the British Ministry of Aviation published in the Journal of the Institute of Navigation.

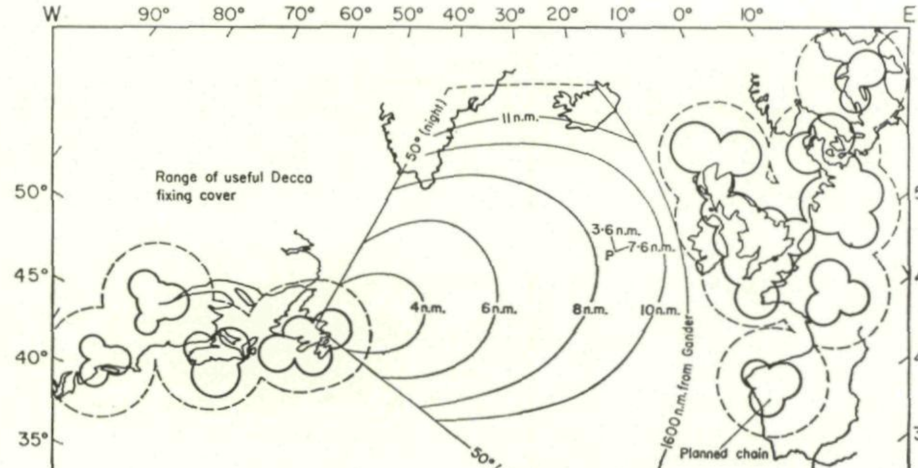

Fig. 1(b). DECTRA plan for the North Atlantic Region

of hyperbolic lines produced by the transmissions of the ground stations A and C crossing them.

It may be necessary to accomplish navigation with three ground stations only. Then A–B is used for obtaining tracking information, and A–C for ranging as shown on Fig. 1b.

The hyperbolic pattern of the base line transmitters A and B is produced by the following transmissions: the ground station A radiates for a period of 9 sec c.w. transmissions at the frequency F_1. This period of transmission is 10 sec in Mark 10 operation. The transmission is interrupted for approx. 0.1 sec according to a fixed schedule, then the transmission is resumed for 0.1 sec, and finally the transmission is interrupted again for a period of 0.5 sec (Fig. 2). By these two interruptions a switch is actuated in the Slave

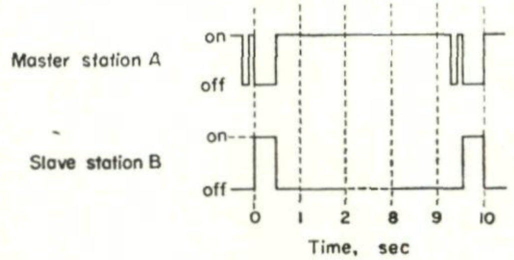

Fig. 2. Transmission cycle of the Master station A and Slave station B of the base line No. 1

station B and in all DECTRA receivers of the users, which effects the phase-locked transmission of the same frequencies F_1 from the Slave station B at the beginning of the 0.5 sec interruption, and at the same time releases in each receiver a circuit for measuring the phase-angle difference between the waves received from A and B. The transmission of the Slave station B is interrupted after a period of 0.5 sec, and the Master station A begins again to transmit for approximately 9 sec. At the same time, the receivers of the users are changed over again for measuring the phase angle of the transmissions from the Master stations. Hence, the frequency F_1 is transmitted alternately from A and B (apart from the signalling period of 0.1 sec in duration). By means of an oscillator installed in B, which is synchronized by the transmissions from A while the transmission of B is interrupted, a phase-locked transmission can be maintained during the 0.5 sec transmission period.

A block diagram of the tracking receiver is shown in Fig. 3. During the transmission period of the Master station A, the F_1 oscillator is synchronized (Fig. 3a). During the transmission period of the Slave station B (Fig. 3b), the phase-angle difference between the phase-locked F_1-oscillator and the wave received from B is measured in the F_1-discriminator. This difference appears at the two outputs of the F_1-discriminator in the form of two capacitor d.c. voltages which are proportional to $\sin\theta$ and $\cos\theta$. These voltages are generated in compliance with the instantaneous phase-angle difference during the 0.5 sec transmission period of the Slave station.

When a proper time constant of the F_1-discriminator output is selected, the phase-angle difference is insensitive to atmospherics of duration less than 0.1 sec, which is normally the case, Thus, already after a period of 0.5 sec, the phase-angle difference can be established. The d.c. outputs are used for controlling the decometer displays, which are maintained at their instantaneous values for 7.5 sec until the next phase-angle measurement is performed.

The hyperbolic ranging pattern, with the foci A and C as shown in Figs. 1a and 1b between the bases 1 and 2, produced by the transmissions of the transmitters A and C are generated by the following transmissions:

Station A transmits the frequency F_1, which is received by the ground station C and thus synchronizes a continuous oscillator. This oscillator produces a new frequency F_2, which is related to the frequency F_1 by a common sub-harmonic. In the special case of the North Atlantic, the following equation applies:

$$F_2 = F_1 \frac{N_2}{N_1} = F_1 \frac{460}{459} = N_2 \, . \, F = 460 \, . \, F$$

The transmission of the frequency F_2 by the transmitter C is controlled in such a manner that there the difference frequency F_2–$F_1 = F$ remains in phase with the sub-harmonic F produced by the division of F_1.

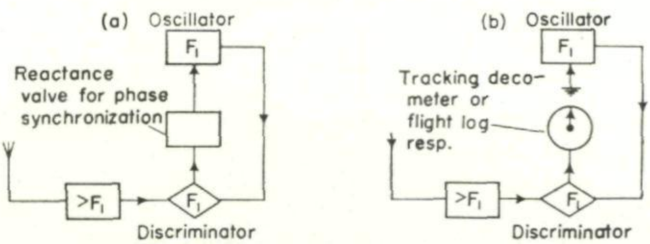

Fig. 3. Block diagram of the receiver for determining the line of position within a lane of the tracking pattern radiated from the No. 1 base line

(a) during the transmission from Master station A

(b) during the transmission from Slave station B

For fine distance measurement, i.e. for the determination of a line of position within a lane of the ranging pattern of hyperbolic lines, the frequencies F_1 and F_2 are received simultaneously by the DECTRA receiver.

Each of these frequencies is fed to an oscillator via a discriminator (Fig. 4). The oscillator is synchronized by these two frequencies. The amplifiers for the frequencies F_1 and F_2 control the phase of the two incorporated oscillators, which then are employed as noise-free voltage sources for the further comparison of the phase angles. The F_1-oscillator is also used for determining the course line of position as described above. The time constant of the phase control circuits of both oscillators is very long. Thus they form an element of high inertia, when rapid variations in phase-angle difference occur. In this way the previously phase-locked signals can be " stored " for several minutes even when the transmissions are

interrupted, or when brief phase variations occur in the received signals due to atmospherics. The frequency drift of the oscillator is less than 10^{-7} over a period of several minutes. The phase control circuit cannot exercise control at a faster rate than 1/50 of a revolution per second of the ranging decometer pointer. The inertia is such that the position display can follow reliably any manoeuvres of fast aircraft up to a speed of 1 Mach (0.3 km/sec).

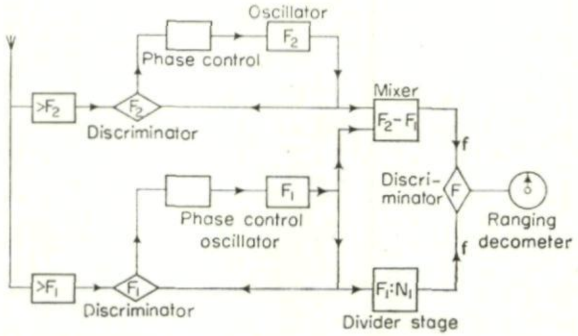

Fig. 4. Block diagram of the receiver for determining the line of position within a lane of the ranging pattern

In order to obtain a range line of position, the frequency F_1 is divided to its subharmonic $F_1/N_1 = F$ and is fed to one side of a ranging decometer, whose other side is fed with the subharmonic derived from mixing of the frequencies F_2–F_1.

The phase-angle difference existing between the sub-harmonics F derived by division on the one hand and by mixing on the other is determined by the difference in the distances from the point of reception to the transmitters A and C. It defines the line of position within the hyperbolic ranging lines between the transmitters A and C in the same manner as it is defined within the hyperbolic tracking pattern by the comparison of the phase angles of the alternating transmissions of equal frequency by the transmitters A and B or C and D respectively.

The determination of the position within the ranging pattern by measuring the phase-angle difference of a frequency F which is 460 times smaller than the basic frequencies F_1 and F_2 may lead to the conclusion that a lane width within the ranging pattern would be obtained which is 460 times greater than that within the tracking pattern (similar to Decca coarse position fixing).

Since, however, the basic frequencies F_1 and F_2, from which the comparison frequency is derived are received from opposite directions the slow phase-angle variation corresponding to the sub-harmonic F along the line connecting the base line 1 (A) and base line 2 (C) is superposed with a fast phase-angle variation, which corresponds to the narrow lane width of the basic frequencies F_1 and F_2. Thus a lane width of approximately 2 km is obtained, which allows a very accurate determination of the distance covered between the two base lines.

These data are valuable in dead reckoning. But in order to obtain an unambiguous fix, the airborne equipment must be adjusted at a known position (for instance the aerodrome of departure). Then further readings remain unambiguous unless reception is interrupted by prolonged and severe interference or fading.

The North Atlantic DECTRA chain operates on the following frequencies.

Frequency	*Lane Width on the Base Line at* $c = 299{,}700$ *km/sec*
$F_1 = 70.3842$ kc/s $= 459F$	2129.035 m
$F_2 = 70.5375$ kc/s $= 460F$	2124.402
$F = 0.153342$ kc/s	

These low frequencies are particularly suitable for the special DECTRA purpose, since the *E*-layer of the ionosphere, which is responsible for the reflection of such waves, is rather stable and thus allows sky wave reception within the entire coverage.

The use by DECTRA and Decca of similar frequencies is an advantage in that many components of the ground installations and of the receivers may be used by both systems.

Errors in the DECTRA system are greatest when ground wave and sky wave (or two sky wave modes) of almost the same amplitude but inversely phased coincide, i.e. at distances of over 1000 km at day, and at distances of over 500 km at night. The stronger absorption of the very long sky waves occurring in summer are detrimental to DECTRA reception, since this system is dependent upon the synchronization over long distances of the base line stations A and C. On the other hand, however, this phenomenon is favourable for Decca which prefers the ground wave. The reduced absorption of the *E*-layer in winter, when the *E*-layer is 90 km in height, has the inverse effect. DECTRA operation is improved during that season while Decca ranges are reduced.

The propagation of the 70 kc/s wave of the DECTRA system occasionally causes fading which, as a rule, is of short duration only. Such fading occurs when the altitude of the *E*-layer varies substantially during dusk and dawn periods. Frequently, no unambiguous phase relationships exist in these interference zones (whose positions vary substantially over 24 hours) because of the vectorial addition of ground and sky waves, especially when both are of equal magnitude; or the phase-angle difference is subject to rapid and considerable variations of up to $\pm\pi$ in magnitude. The ranging circuits will not accept such variations and are switched automatically to a device which continues to operate automatically on the speed previously displayed until the fast variations in the phase-angle difference have ceased and the control circuits of the receiver oscillators F_1 and F_2 again accept the received frequencies (see also Repeater unit, Chapter 2.08). This phenomenon affects the tracking pattern to a lesser degree, for the two transmitters of a base line transmit the same frequency and so the sky wave from these two stations is correlated.

When the signal strength is reduced, alarm lamps for F_1 and F_2 respectively on the DECTRA receiver indicate this condition.

As soon as reception returns to normal, the oscillator F_1 or F_2 respectively is synchronized again by the input voltage. It may happen that its phase angle then jumps by $\pm \pi$ and no longer remains locked to the correct lane so that all subsequent fixes are obtained in one of the adjacent lanes and thus are displaced by one lane (width 2.1 km). Apart from the critical zones,

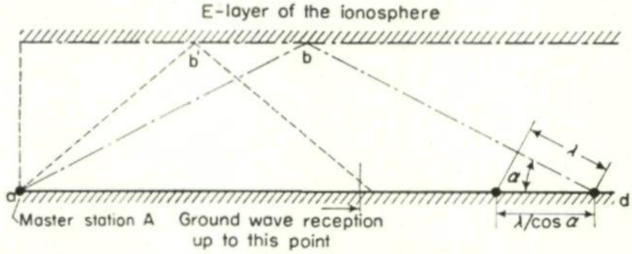

Fig. 5. Explanation of the increase in the width of the ranging lanes

where sky waves and ground waves which are almost equal in amplitude coincided for the first time, the following deviation from normal propagation occurs:

At night the reflection from the *E*-layer (height approximately 90 km) of the waves is considerably greater than at day (height approximately 70 km). Hence, the sky wave propagation is more intense at night; it is not parallel to the surface of the earth but at an inclined direction (from b to d in Fig. 5). The loci of equal phase-angle difference are no longer spaced by a distance of $\lambda/2$ but by $\lambda/2 \cos \alpha$, i.e. the lane width is increased. This increase is of a systematic character; it does not occur prior to the first hope and is dependent upon the height of the *E*-layer. Hence, it is dependent upon the time of the day and on the season.

When the transmitters located on Newfoundland radiated a power of approximately 2 kW, approximately 5 μV/m were available at day, and 30 μV/m at night for synchronizing the station C located in Great Britain. These measurements were made in summer, i.e. in that season most unfavourable for propagation.

3. ACCURACY AND RANGE

A great number of propagation tests performed previously with the 70 kc/s range of frequencies showed that the phase-angle difference varies only by $\pm 0.25\pi$, when *different* sky waves are received which are added vectorially. Based on these tests the effective ranges shown in Fig. 1a have been calculated for two radial errors which are not reached at 95 per cent of the time. Intensive studies of the navigational errors of the North Atlantic DECTRA chain consisting of three ground stations were made by the A.A.E.E. (Aeroplane and Armament Experimental Establishment of the British Ministry of Aviation) and major airlines on numerous flights of jet aircraft and conventional civil aircraft.[3]

The maximum standard deviation as dependent upon the heading observed

at these flights during summer is shown in Fig. 1b.[4] The standard deviation of the position is also dependent upon the direction. The maximum position error at P of Fig. 1b is 8.2 n.m., but it is 7.6 n.m. along the tracking pattern, and 3.6 n.m. along the ranging pattern. By taking the course into consideration smaller position errors are obtained. The accuracy is better in winter.

Ranging errors of one or several lanes may occur in the critical interference zones and in conditions of severe atmospherics. Such errors normally can be recognized and corrected by comparing the position indicated with the position obtained from dead reckoning. The use of very stable phase-locked receiver oscillators for the frequencies F_1 and F_2 (cf. Fig. 4) largely eliminates such lane errors.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

When the flight departs from an aerodrome which is located within the DECTRA coverage, the stylus of the Flight Log is set on the point of departure. If, however, the aircraft is provided with a combined Decca/DECTRA installation, and when the first leg of the flight is accomplished within the coverage of a Decca chain, change-over from Decca to DECTRA operation is performed before the aircraft leaves the coverage of the Decca system, whose accuracy is greater. Change-over or switching on is performed by means of a remote control unit.

The receiving unit is ready for operation approximately 10 min after it has been switched on.

When the aircraft enters the coverage of the DECTRA system without change-over from Decca to DECTRA operation, the stylus must be set to the instantaneous position obtained by dead reckoning or other radio navigation aids. Since the DECTRA system is ambiguous, the position must be known accurately enough to that the stylus can be set within the correct lane of the tracking and ranging patterns; otherwise the positional error so caused remains effective until re-adjustment is accomplished by reference to position information obtained from other navigational aids. The tracking error is increased with the distance from the pair of stations. *En route* checks of the stylus setting are accomplished by reference to the two DECTRA decometer displays of range and track.

When the landing is performed with the coverage of a Decca chain and a combined Decca/DECTRA airborne equipment is available, positional errors of the DECTRA system can be eliminated by changing over to Decca operation. Thus such accuracy of positional information is obtained as is required in airway navigation and in particular in the terminal areas.

Five basic charts for the Flight Log cover the North Atlantic region significant for DECTRA navigation. Two charts are required only for one crossing of the Atlantic. Some distance and course information of the major alternate aerodromes is given on the back of each chart. Such information is visible only upon switching on the illumination provided behind the chart.

The use of the Flight Log allows continuous position reporting and calculation of the ground speed. The magnitude of deviation from track can be read immediately at any time.

In order to accomplish navigation within the interference zone of the ground wave and the sky wave, the DIAN system should be used (Decca Integrated Airborne Navigation), which, after change-over, plots on a chart the positions derived from Doppler navigation.

5. GROUND INSTALLATION AND AIRBORNE EQUIPMENT

Ground Installation

A DECTRA ground station comprises the same equipment as a Decca station: three oscillator stages, one transmitter output stage, standby transmitter, automatic change-over facility and incorporated monitoring equipment.

At present, the power transmitted from each of the Master and Slave stations is 12 kW. It is intended to increase the transmitter power to 20 kW. The power required is approximately 40 kVA.

The transmitter installation costs approximately 300,000 DM (FOB, U.K.).

A set of service valves costs 12,000 DM and the monitoring equipment costs approximately 25,000 DM. The aerial costs (without installation) 212,000 DM (FOB, U.K.).

The DECTRA aerial is larger than a Decca aerial and consists of a three-mast top loaded system. The counterpoise consists of 100 wires each 183 m long.

The total price of a ground station of 1,200,000 DM as stated in Table 4.3 includes 650,000 DM for the following items:

Construction of the transmitter building, construction of a building for the operators, purchase and preparation of the site, erection of the rhombic aerial and installation of the counterpoise and installation of the aerial and costs of the commissioning tests, which are indicated in Table 4.3 in terms of man-hours and physical magnitudes. Two engineers and three operators are required for the current operation of a ground station.

Assembly and placing into service of a pure DECTRA station requires approximately 1700 hr, and approximately 1800 hr are required in the case of a combined Decca/DECTRA ground station.

The commissioning tests of a ground station require approximately 1000 hr. These data refer to a DECTRA station not combined with Decca. The annual current operating costs of a ground station are:

costs of valves	18,000 DM
power consumption	240 MWh
maintenance costs, approximately	10,000 DM

Airborne Equipment

The receiving aerials are the same as used for Decca; electrical charging by raindrops is provided against. At present two different models are tested.

A DECTRA airborne equipment is always installed together with Decca and hence it contains four decometers, only two of which are used for DECTRA navigation.

The prices of Table 1 refer to FOB, U.K. The estimated annual servicing costs amount to approximately 3000 DM.

All equipment not needed in the cockpit is mounted in standard racks,

where it is protected from mechanical shocks. Part of the equipment can also be used for Decca navigation.

On completion of experiments carried out at present the production is planned of multi-channel Decca/DECTRA-receiver.

Table 1. *Normally required Decca-DECTRA Receiving Equipment*

Unit/Model	*FOB Price in TDM*	*Weight (kg)*	*Overall Dimensions width × height × depth (cm × cm × cm)*
Receiver Mark 7B, model 876	15.1	26.8	60 × 20 × 40
DECTRA Receiver Model 856	7.65	14.0	41 × 20 × 41
Power Pack 859, for common use by Decca and DECTRA	2.06	15.0	20 × 20 × 40
Computor 830	8.9	7.5	15 × 20 × 41
Ranging decometer 867	0.7	0.5	7.3ϕ × 9.5
Display head 331B	3.47	4.5	14.3 × 14 × 32
Control box 857 for DECTRA computor (2nd line of this Table)	0.65	0.5	14.6 × 6.2 × 7.6
Control box 839 for Flight Log computor	0.89	1.2	14.6 × 13.7 × 6.4
Total additional DECTRA equipment without display head 331B	(depends on aircraft model in which the Decca-DECTRA receiving equipment is installed)		
Three decometers model 273	Remarks, see Table 2 in 2.08		
Two aerial-amplifiers model 3089			
Receiver control box model 278			

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2.10. STANDARD-LORAN

(LOng RAnge Navigation)

E. Kramar

1. GENERAL INTRODUCTION

The LORAN system is based on an American proposal made in 1940.[1] At that time it was intended to design such a system for the v.h.f. band. At approximately the same time a similar method was proposed in Great Britain and led to the development of the GEE system operating in the frequency band from 20 to 85 Mc/s. In 1941 tests commenced in the U.S.A. with 8.5 and 2.9 Mc/s: the objective was to increase the range of the ground wave and also to utilize the sky wave reflected from the *E*-layer in order to obtain a long-range navigation system. Already in 1942 ground wave ranges of up to 700 n.m. and sky wave ranges of up to 1400 n.m. across sea were reached with transmitters radiating a peak pulse power of 100 kW. The fixing accuracy obtained was extremely great. Measurements made with frequencies between 1.75 and 1.95 Mc/s produced most favourable results, since at these frequencies the height variation of the reflecting *E*-layer is negligible.

Already in 1943 LORAN was applied for marine navigation and later also for air navigation in the North Atlantic region. In 1944 the SS LORAN system (Skywave Synchronized LORAN) was developed, in which the ground stations were no longer synchronized by ground waves (maximum possible distance 600 n.m.) but by sky waves, and a separation of the interlocked stations of up to 2000 n.m. became possible. Although this method could only be utilized during night-time, and although the accuracy was slightly less than with ground wave operation, it was applied successfully in Europe and Japan during the last year of World War II.

Since then LORAN has been developed further, in particular with regard to accuracy of ground station synchronization and simplification of receiver operation by the application of computers. At present LORAN stations constructed during World War II can be used by ships and aircraft for navigational purposes over a large portion of the globe (Fig. 1).

The frequency band 1750–1950 kc/s used by LORAN lies in the frequency range allocated exclusively to fixed and mobile communication services in Region 1 (Europe, Asia, North Africa).[9] In this region the Iceland–Faeroes–Hebrides LORAN chain is operated. The problem of getting official recognition for the LORAN frequencies was discussed by the Administrative Radio Conferences held in Geneva in 1949[10] and 1951.[11] When the frequency problem of STANDARD-LORAN was discussed again at Geneva in 1959 no world-wide agreement was reached. Thus LORAN navigational transmitters of Region 1 may operate temporarily on the single frequency of 1950 kc/s provided that their operation is regulated by a

special agreement with such administrations whose radio operation would be adversely affected by such LORAN transmitters. In Region 2 the 1800–2000 kc/s frequency band is reserved for Standard-LORAN. In Region 3 the frequencies of 1850 kc/s and 1950 kc/s are reserved for Standard-LORAN.

As early as 1944 attempts were made to transfer the LORAN principle to low frequencies (180 kc/s) in order to obtain greater ranges, especially in the Pacific. These experiments, however, were interrupted after the war. At about the same time it was suggested to synchronize the r.f.-carrier of the pulse transmitters and to apply phase measurement techniques to the receiver in order to increase the measuring accuracy. These proposals were repeated in 1955[2] and led to the development of the LORAN–C system (cf. Chapter 2.11).

2. SYSTEM DESCRIPTION

The Standard-LORAN system is based on the measurement of the time difference between pulses which are radiated synchronously by a pair of transmitters located at a distance of several hundred kilometers (base line). The loci of equal time difference (or distance) are two symmetrical hyperbolae with the transmitters being located in their foci (ambiguous). By delaying the emission from the substation (B) until the pulse from the Master (A) has passed the site of the substation, the hyperbolic position lines become unambiguous, since the pulses of transmitter A cannot be mistaken for pulses of transmitter B. The pulse recurrence of B is synchronized by A. In order to facilitate the indication aboard, the pulses of the B transmitter are delayed by half the time between two pulses from A as received at B.

The signals from a pair of ground stations are displayed on an oscilloscope with two horizontal traces synchronized with half the recurrence rate characteristic for the stations of interest. The leading edges of the pulses constitute the criterion for the time measurement. Several transmitter pairs having different pulse recurrence rates can be accommodated on the same carrier frequency, because irrelevant pulses drift across the stationary display of the correct pulses without impairing the measurement.

Four carrier frequencies between 1750 and 1950 kc/s are used. For the modulation of each carrier three basic pulse recurrence rates are available. Each basic rate is further subdivided into a group of eight by individual frequency differences in the order of a fraction of a cycle per second. The three groups and the individual shifts of their eight frequencies are:

S Group 20 c/s with a shift of 1/25 c/s (S-rate)
L Group 25 c/s with a shift of 1/16 c/s (L-rate)
H Group $33\frac{1}{3}$ c/s with a shift of 1/9 c/s (H-rate)

This arrangement provides for $4 \times 8 \times 3 = 96$ different available channels. The transmitted pulse has a width of 45 μsec and a rise time of 10 μsec.

A measurement is made in the following manner: On the oscilloscope the pulses from the B transmitter (lower line) are placed with their leading edges vertically below those from the A transmitter (upper line); in older equipments the time difference corresponding to this adjustment had to be determined by a special measurement procedure. In more modern receivers

Fig. 1. LORAN Transmitters Station.

To face page 114

a direct reading is obtained from an electronic counter, which indicates the time difference in three decades. For further details of the transmission and receiving techniques used see refs. 1, 3, 4 and 8 (Fig. 2).

As was mentioned above, a frequency around 2 Mc/s was chosen for Standard-LORAN, since the *E*-layer of the ionosphere reflecting such

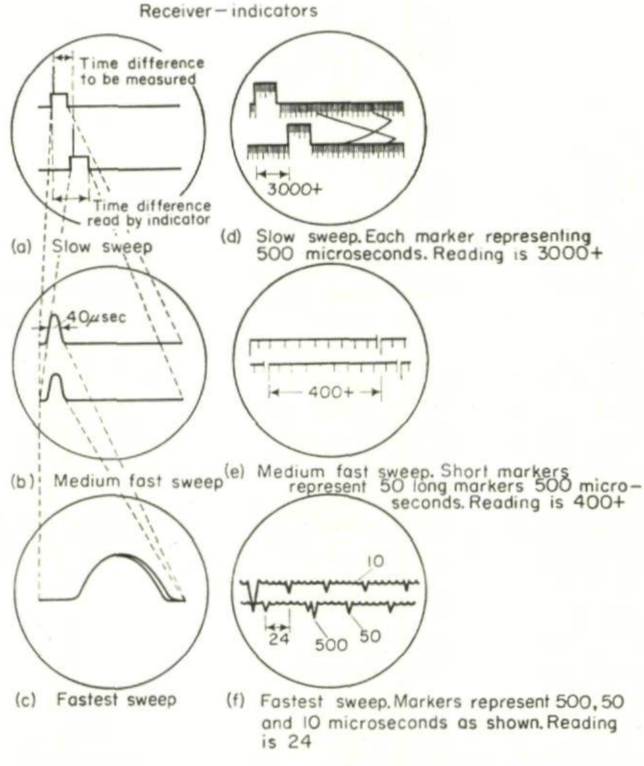

Fig. 2. (a) Slow-trace pattern with signals; (b) medium-trace pattern with signals; (c) fast-trace pattern with signals; (d) slow-trace pattern with 50- and 500-μsec markers, showing time difference of 3000 μsec plus approximately 500 μsec, (e) medium-trace pattern with 50- and 500-μsec markers, showing additional time difference of 400 μsec plus approximately 30 μsec; (f) fast-trace pattern with 10-, 50-, and 500-μsec markers, showing the time difference of 24 μsec. Total time difference is 3424 μsec. LORAN-Measuring method[1]

frequencies maintains a rather constant height ($\pm$ 2.5 km at an altitude of 100 km). Due to international regulations this frequency band is not available for navigation purposes throughout the world; it is reserved, especially in region 1, for marine communication services.

A disadvantage of Standard-LORAN, as far as frequency economy is concerned, is the large frequency spectrum inherent in pulse modulation and the consequently large receiver bandwidth required. This disadvantage is compensated for by the fact that LORAN is the only radio navigation system which, by virtue of the pulse modulation and the cathode-ray tube

display, allows separation of ground wave and sky wave components and, at the same time indicates the reliability of the signal received.

In spite of the small number of carrier frequencies a great number of channels is available due to the different pulse repetition rates, making the narrow frequency band from 1.75–1.95 Mc/s sufficient for a world-wide application of this system.

3. ACCURACY AND RANGE (COVERAGE)

The overall accuracy of LORAN is determined by the geometry of the system, the position of the observer within the service area and by the accuracy of the time measurement. The time measurement accuracy is dependent upon the synchronization of the ground stations, the time difference measurements performed aboard and the propagation conditions. The overall time measurement accuracies can be assumed to be 1–5 μsec (standard deviation), when the ground wave component is used. When the sky wave component is used, the tolerances caused by variable propagation are increased; their magnitude is a function of the time of the day, season, terrestrial latitude, sun spot activity, etc. Thus the standard deviation may be increased by several microseconds. The inaccuracy not exceeded for 95 per cent of the time is therefore said to be 0.2–0.6 per cent of the distance of the receiver from the center of the base line.

The average range (coverage) of the ground wave amounts to 550 n.m. across sea, assuming 100 kW pulse peak power and outside interference fields below 25 μV/m on the receive side.

In equatorial regions the atmospheric noise level is much higher and reduces the range to 400 n.m. during night-time because a useful signal of 250 μV/m is required. In arctic regions a range of 800 n.m. is obtained both at day and at night, with undisturbed ground wave field strength of about 1 μV/m.[1]

According to other publications[4] a range across sea of 700–800 n.m. at an average accuracy of 1.5 n.m. (over land 200–500 n.m.) is obtainable with ground waves during daytime. The corresponding values for night operation and utilization of the sky wave are: 1400 n.m. over sea and over land with an accuracy of 5 n.m.

The ground wave range is increased by 100–200 n.m. with a peak pulse power of 1000 kW.[4]

The detailed computation of the error circle is given in Part 3 of this report: " Range (Coverage) and Accuracy of Radio Navigation Systems ".

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The radio coordinates supplied by LORAN are hyperbolic lines of position whose ordinal number corresponds to the value of the time difference measured on the receiver. Normally each time a fix is required a new individual measurement has to be taken. There are, however, also automatic continuous indicators available. Such indicators follow automatically the changes in time difference readings caused by the craft moving relative to a pair of stations to which the receiver is tuned. The instantaneous values are indicated directly.[7] The geographical position of the radio coordinates is obtained from special charts provided with a suitable superimposed

hyperbolic grid system. When no special chart is available the radio coordinates indicated can be used for navigational purposes only when a hyperbolic line of position accidentally would coincide with the planned course.

Operation of the equipment is relatively simple when the ground wave clearly predominates. However, profound experience is required for recognizing the first incident sky wave at long ranges and in particular for distinguishing ground waves from sky waves within the intermediate regoin and for superimposing both leading edges, which is so important. Errors in allocating corresponding leading edges (ground wave and first hop sky wave, or first and second hop sky wave respectively) can be reduced by prolonged observation of the cathode-ray tube screen.

When the received signals are observed on the cathode-ray tube, position finding can be performed up to a signal-to-noise ratio of approximately 2 : 1.

5. GROUND STATIONS AND AIRBORNE (SHIPBORNE) EQUIPMENT

Ground Stations

A Standard-LORAN chain used for navigational purposes consists of at least three transmitting stations located at a distance from each other of approximately 200–400 n.m. The peak pulse power of the transmitters is 100 kW, the line load is approximately 15 kVA (30 kVA at a peak pulse power of 1000 kW). The transmitters are equipped with synchronizing facility and monitor equipment.[4] The central (master) transmitter of such a chain radiates two pulse groups by means of which the two slaves are synchronized on the same carrier with one pulse group each.

There are also chains consisting of two pairs of stations of Masters and Slaves.

The transmitters are operated manually; automatic synchronization of the Slaves is being developed.

Site requirements: approximately $(200 \times 200)\ m^2$ per transmitter station.

Antenna: either of the T-type, 30 m high, or steel towers 33 m or 100 m high, respectively.

Airborne (Shipborne) Equipment

Special receivers with four fixed channels (1750, 1850, 1900 and 1950 kc/s); bandwidth 40 kc/s; cathode-ray tube and facility for time difference measurement; since recently, electronic counters are available. Weight of a modern marine receiver Model LR 8803 (RCA) approximately 50 kg, price in Germany approximately 15,000 DM.

Aboard aircraft Standard-LORAN receivers of the war years are still used extensively. An example of a modern airborne receiver is the EDO receiver (see Table 4.3).

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2.11. LORAN-C

E. Kramar

1. GENERAL INTRODUCTION

Shortly after the implementation of Standard-LORAN attempts were already made to apply the same principle to low frequencies.[1]

The low-frequency range (100 kc/s) was chosen because of the far better propagation characteristics of the ground wave, by means of which ranges of up to 1000 n.m. and more were expected to be obtained. Detrimental factors, however, are the inferior efficiency of antenna arrays of reasonable dimensions, the long transient time of the circuits and antennas and the high atmospheric noise level in the low-frequency band. Tests made in the U.S.A. in 1944–45 showed a very good positional accuracy with ground waves at ranges of up to 1200 n.m.[1] An antenna cable of 400 m in length was fixed to a captive balloon; later this cable was replaced by a steel mast 200 m in height; the test frequency was 180 kc/s and the pulse width was 300 μsec. The tests were interrupted after the war since the inadmissibly wide frequency spectrum of the pulses did not seem to justify the practical application of the low-frequency LORAN system.

During the period of 1952–1957 the USAF together with the Sperry Gyroscope Corporation thoroughly studied the system which was originally named CYCLAN, later CYTAC and finally LORAN-C operating on the 90–110 kc/s frequency band.

Under normal noise conditions and with transmitters emitting a peak pulse power of from 60–200 kW accuracies were obtained at ranges of up to 1200 n.m. over land as illustrated in Fig. 1 (cf. ref. 3). It is pointed out that these accuracies coincide to a great extent with the predicted values.

A particular feature of LORAN-C is that base-line lengths (distance between ground stations) of from 600–1000 n.m. are permissible because of the new frequency range. When four transmitters are located on the corners of a square, an area of optimum coverage and maximum positional accuracy is obtained. Other hyperbolic navigation systems which do not allow separation of ground waves and sky waves can operate only with substantially shorter base-line lengths (approximately 100 n.m.)[7]. Hence, area coverage is also reduced substantially. A number of such square chains (Fig. 2) have been suggested for the U.S.A. The position error distribution curve indicates that the system promises to be sufficiently accurate also for medium-range navigation. For the North Atlantic region a chain configuration has been suggested as illustrated in Fig. 3.[3,4]

In 1957 the U.S. Government built a LORAN-C chain on the East coast (Fig. 2). The Master station was built on Cape Fear (Carolina Beach) and the Slaves at Jupiter Inlet (Florida) and Martha's Vineyard (Mass.). The U.S. Coast Guard started trial operations and asked the firm of Jansky and

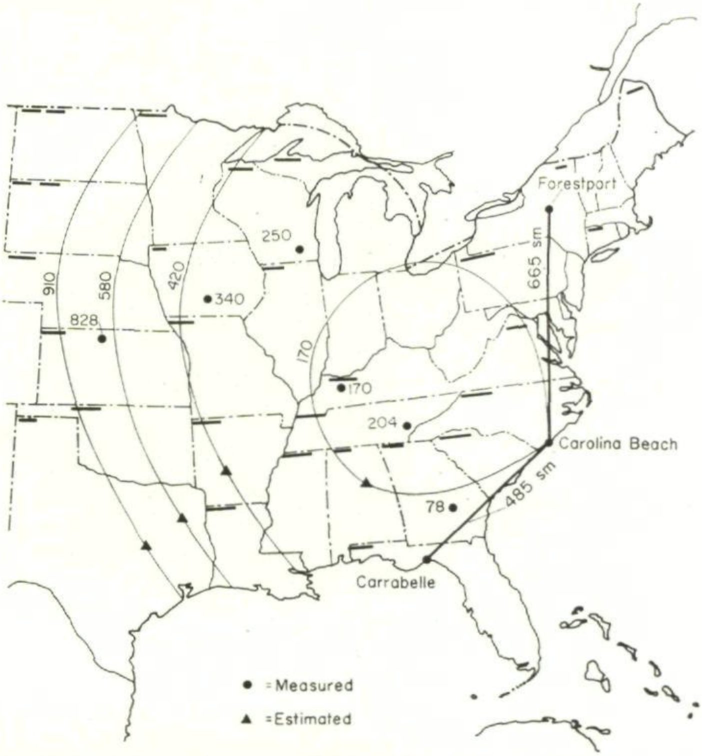

Fig. 1. Estimated and observed LORAN-C fix accuracy in ft (95% *probability*)

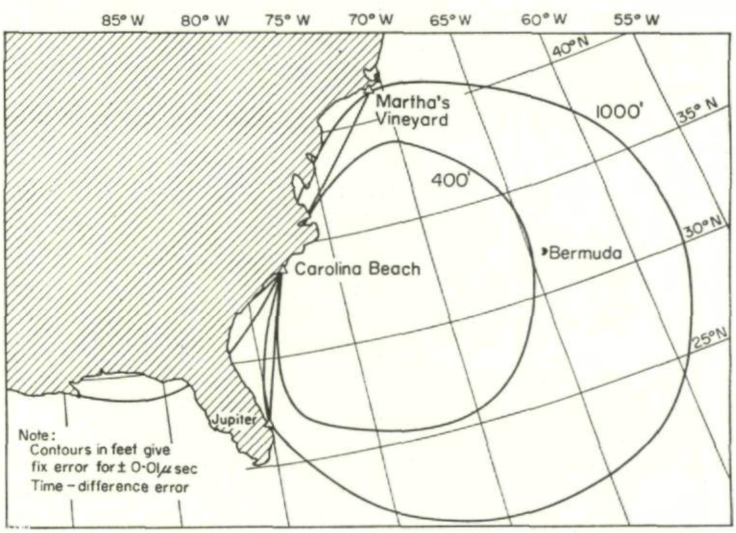

Fig. 2. Accuracy Contours—East Coast of United States

Bailey, Inc., to conduct thorough tests and measurements during the period of 1958–59.[6]

In 1959 the U.S. navy built another LORAN-C chain with the transmitters located at Cantazaro, Istanbul, and Marble Arch (Lybia), and in early 1960 another European chain for the northern North Sea with the transmitters on Iceland, Faeroes and Northern Norway.[7] These three chains are permanently in operation and keep within the accuracy limit for 98–99 per cent of the time.

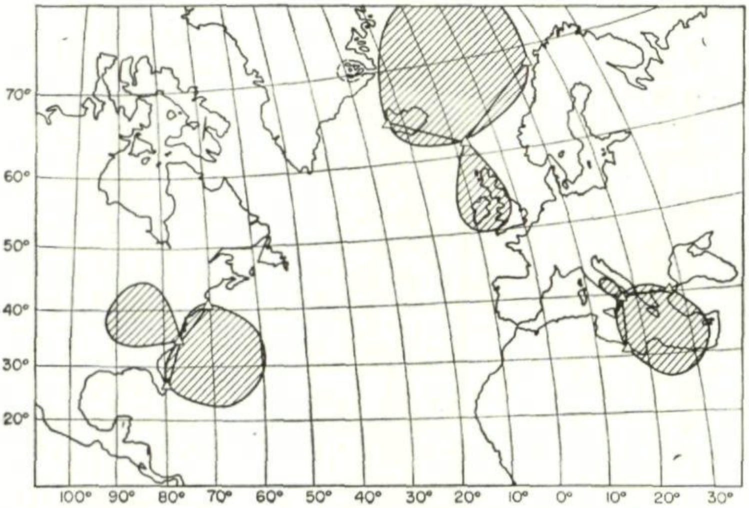

Fig. 3. Existing Loran-C Coverage—1960

Recently the application of direction finders has been suggested which would allow the separation of ground waves from sky waves by using the LORAN-C receiver technique in order to obtain with the former mode bearings of LORAN-C stations which are free from night effect. In this way fixes could be obtained in places where only two stations of a LORAN chain or one station each of two independent chains can be received. Mention should be made of the fact that with the aid of LORAN-C, chronometer corrections of an accuracy of fractions of a thousandths of a second can be made when one's own position is known and when the transit time from the Master station is taken into account; for this purpose a receiver is said to suffice which is considerably more simple than the conventional LORAN-C equipment.[7]

2. SYSTEM DESCRIPTION

LORAN-C applies the two following methods for measuring the distance by means of radio waves:

As in Standard-LORAN the arrival of the pulses emitted from two stations are used for " coarse " time difference measurement, with the lines of equal time difference being hyperbolae. " Fine " time difference measure-

ment is accomplished by phase difference measurement of the carrier frequencies. The ambiguity is approximately 1 n.m. on the base-line of two transmitting stations emitting a 100 kc/s carrier. The ambiguity is eliminated, however, by the coarse time difference measurement. Thus, the positional accuracy of LORAN-C is ten times better than that of Standard-LORAN because of the fine time difference measurement facility.

LORAN-C differs from Standard-LORAN in the following aspects:

(*a*) By a precisely defined progress of the pulse rising edge and by precisely synchronizing the carrier frequencies filling the periods between the pulses with one another and with the rising edge it becomes not only to achieve an unambiguous coarse fix by measuring the pulse rising edges (similar to the Standard-LORAN system) but also to obtain a fine fix independently of the sky wave by a carrier frequency phase comparison.

(*b*) A considerably longer range of the ground wave, especially over land, is obtained by the lower frequencies (approx. 100 kc/s compared with approx. 1800 kc/s of Standard-LORAN).

(*c*) The receiving station operates fully automatically and provides continuously position information by measuring simultaneously two transit-time differences; provisions are made at the receiver output for connecting directly to it automatic chart devices, computers or other equipments.

(*d*) Each LORAN-C station transmits groups of eight pulses spaced by 1 μsec each. By storing them in the receiver one obtains an improved signal-to-noise ratio, and thus the maximum range of the system is increased considerably.[8]

(*e*) The phase of the carrier frequency oscillations of individual pulses within a pulse group is either kept constant or it is changed by 180° according to a pre-determined code. A different code is used for Master and Slaves. By comparing these carrier oscillations coded by phase keying with a locally generated reference of the same kind, one removes that portion of the sky wave errors which is due to pulse echoes being delayed considerably by multiple reflection and which then are received when the next pulse arrives. The phase coding facility serves in addition the purpose of station identification. It is a condition for de-coding that there is a stable synchronization between transmitter and receiver, which is obtained by several special measures.[8] Even when acceleration is great (airborne reception) the automatic functioning of the equipment is ensured by feeding in course and speed information.[9]

The physical principle is essentially similar to that used in Standard-LORAN. For also in LORAN-C the emission of pulses by the Slaves is delayed until there is no ambiguity with regard to the pulse envelope measurement within the service area. The additional phase comparison of the carrier frequencies of the pulse groups received sequentially is accomplished by modern storage techniques (synchronization of a local oscillator). Most modern receiver design and evaluation techniques are used to achieve automatic reception. The application of a synchronous detector (quadrature detector) makes a sharp input selection (25 kc/s at 3 dB) unnecessary.

A band pass filter with steep rising edge is provided for protection against power transmitters operating close to the 90–110 kc/s frequency band. Protection against interfering transmitters operating within the receiving band can be obtained by narrow-band blocking filters.

Further bandwidth restriction is obtained in the evaluation system in that the fine measuring system is coupled mechanically to the coarse system by means of a differential gear. Coarse fixing (transit-time difference of the pulse envelope) need be done only when the receiver is switched on, unless reception fails for a certain period of time. Practical experience shows that both types of measurement should be performed continuously so as to check the proper functioning of the receiver.[9]

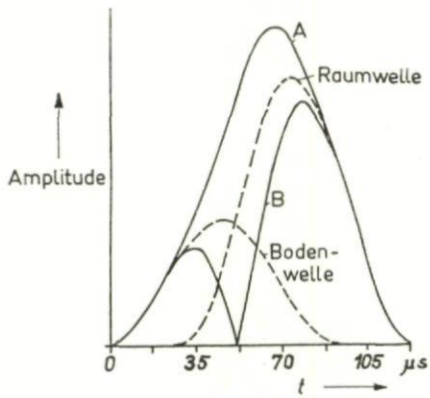

Fig. 4. Complex ground and sky wave pulses, (A) in phase, (B) in opposite phase

The pulse rise time from zero to peak amplitude is approx. 75 μsec, since the sky wave pulses are to be expected at an interval of not more than 35 μsec (Fig. 4) the processing is performed during a 30 μsec rise time by means of a thyratron. Appropriate pulse shaping at the transmitting end places the turning point of the rising edge at this position so that both the coarse and the fine measurement can be performed at exactly that point of time determined by the double difference of the rising edge.

The circuits employed are explained in the literature.[3,8] Reference 8 contains a detailed report on the pulse coding method with double or eight pulses and on the design of the transmitter and receiver circuited.

With sky wave reception at long ranges—without ground wave—the carrier phase measurement can be used for fine fixing purposes only if certain requirements are satisfied.[6]

The pulse recurrence frequencies of LORAN-C are 10, 12, 5, $16\frac{2}{3}$, 20, 25 and $33\frac{1}{3}$ groups per second. Some of these recurrence frequencies agree with those of LORAN-A so that LORAN-C stations can be received with normal LORAN receivers if a frequency converter changing 100 kc/s into 1800 kc/s is placed before the receiver. It is not possible, of course, to make use of the big advantages of the LORAN-C system (fine fixing, automatic operation) with the aid of such an additional equipment; the

accuracies obtainable are even lower than those obtained when Standard-LORAN stations are received.[4,5]

The designers of the LORAN-C system claim that the pulses are designed so that 99 per cent of the spectral energy is within a frequency band of 20 kc/s. Thus the frequencies used by LORAN-C are just within the frequency band of from 90–110 kc/s allocated by the Radio Regulations of Atlantic City 1947 for radio navigation aids.

Thus LORAN-C will be operated on one single carrier frequency only: 100 kc/s. The ground stations of a chain are distinguished by a known shift with respect to time of the pulse transmissions. The chains are distinguished by different pulse groups and pulse repetition rates. By these measures and by pointing out the great advantages of pulse-keying techniques, the designers of LORAN-C intend to meet the reproach of using too wide a frequency spectrum. Thus the 100 kc/s carrier can accommodate 288 channels separated with respect to time, but only 50 are required for a world-wide coverage by LORAN-C.

The data suggested for LORAN-C are listed in Table 4.1 " General Information on Navigation Systems ".

3. ACCURACY AND RANGE (COVERAGE)

The overall system accuracy of LORAN-C with respect to the ground wave is claimed to be $\pm$ 0.25 μsec for 95 per cent of the time, with the distance between the transmitting stations being approximately 1000 km. It is not limited by receiving and processing techniques or by instrumentation ($\pm$ 0.05 μsec), but by time-difference errors as caused by irregular propagation of the ground waves. These fluctuations of the propagation speed of waves due to meteorological influences could be taken into account to some degree in station synchronization. For this purpose the time-difference of pulse groups between Master and Slave, and vice versa, are measured continuously. A corrective factor for the Slaves can be obtained from such slow fluctuations. When the transmitters are installed at the corners of a square of approximately 600 n.m. lateral length, the radius of the circle of uncertainty should be better than approximately 75 m.[2,3,4]

With a pulse peak power of approximately 60 kW and top-loaded antenna masts (200 m high) ranges are expected over land of 1200 n.m. and over sea of 2000 n.m. It is claimed that the range of sky waves is 3500 n.m. with the radius of the circle of uncertainty being increased ten times.[4] Since the receiving station operates automatically, indication is continuous.

As was mentioned earlier, the report in ref. 6 contains much statistical material on the accuracy and range of the Eastern U.S. chain which was obtained also at an observation station on the Bermudas at a distance of approx. 1200 km. The average standard deviation for 15 min is approx. 0.04 μsec, for an 8 hr period the average annual mean is 0.12 μsec. It is emphasized that no corrections were applied which would have been possible due to the predictable changes in the propagation conditions. At the range of approx. 650 n.m. a positional accuracy of 105 ft radius for 50 per cent of the cases was obtained for a 15 min average, and for 95 per cent annual average the radius was approx. 800 ft.

Additional range and accuracy data of interest are contained in ref. 9. With a signal-to-noise ratio of the signal amplitude at the moment of measurement (at the turning point of the rising edge) of -20 dB the following operating ranges were observed:

(*a*) winter night 1450 n.m.
(*b*) winter day 1600 n.m.
(*c*) summer night 1250 n.m.
(*d*) summer day 1300 n.m.

These values refer to 100 kW peak pulse power over sea. The improved daylight values are due to the difference in the atmospheric noise level on the Bermudas. The same report also mentions the large differences in the shortest delay between sky wave and ground wave pulses for the first skip distance: over sea at night 54 μsec, at day 39 μsec, over land at night 47 μsec, at day 32 μsec.

In Part 3 of this report (Accuracy and Range of Radio Location Systems) possible transmitters locations are indicated.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The radio coordinates provided by LORAN-C are hyperbolic lines of position which are indicated directly as distance difference values. Since the receiver indicator is of the automatic type, indication is assumed to be accomplished continuously. Operation of the receiver then would be much simpler compared with Standard-LORAN equipment. According to ref. 3, the time-difference is indicated directly on a counter. The respective hyperbolic line of position will then have to be found on a special chart provided with a suitable grid system. The position is defined by the intersection of two hyperbolic lines of position.

Computers are being developed for converting hyperbolic data into Rho–Theta or X–Y coordinates; they would allow an immediate pictorial position display.[3] An ICAO document[4] states: " LORAN-C provides semi-automatic, continuous tracking and will be designed to present such information as desired by the user ".

5. GROUND STATIONS AND AIRBORNE (SHIPBORNE) EQUIPMENT

The site and building requirements are essentiallly the same as for Standard-LORAN. It is shown in ref. 4 that the costs for the whole ground installation with approx. 60 kW radiated peak pulse power and a top-loaded aerial tower of 200 m in height (24 guys of 200 m in length each in a circle of approx. 600 m in diameter around the aerial tower) and including the counterpoise (180 radial wires of approx. 300 m in length) and buildings are approximately twice as high as for a Standard-LORAN installation.

The various literature references indicate that up to now only few receivers have been built for test purposes. The price (double receiver for direct indication of the radio coordinates, without computer for position indication) is $25,000 to $30,000.

In April 1961 new data became known of the prototype of an airborne

double receiver: Receiver dimensions including processing and indicating unit:

$17 \times 40 \times 48$ cm ($7\frac{5}{8} \times 15\frac{3}{8} \times 19\frac{9}{16}$ in.)

Dimensions of the power supply unit:

$17 \times 12 \times 48$ cm ($7\frac{5}{8} \times 4\frac{7}{8} \times 19\frac{9}{16}$ in.)

Dimensions of the aerial matching transformer:

$7.6 \times 10.2 \times 10.2$ cm ($3 \times 4 \times 4$ in.)

Total volume:	1.75 ft^3 = 50 l.
Total weight:	75 lb = 34 kg
Power intake:	110W, 115V, 400 ~ + 10W, 28V.

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2.12. THE RADIO MESH SYSTEM

(Radio-Mailles)

H. SCHUCHMANN

1. GENERAL INTRODUCTION

THE Radio-Mailles System, in English known as the Radio Mesh System or the Radio Web System, was suggested by Pierre Gaudillère.* In France it is being developed by the Société Francaise des Télécommunications, in the U.S.A. by Stavid Engineering Incorporated. It is a hyperbolic navigation system where a low-frequency modulation of the transmitters is used for creation of hyperbola systems. Contrary to usual hyperbolic systems, slightly different modulation frequencies are used. Thus a moving interference pattern is produced. The hyperbolic lines, called " isophases " by Gaudillère (equiphase lines), move at a certain speed which is dependent upon the modulation frequencies selected. They cover the whole area between the transmitting stations.

The Radio Mesh System[1–14] is proposed for the following application-with carrier frequencies suitable to air and marine navigation:

(*a*) Navigation and position fixing on board.

(*b*) Traffic control with the indication of the position of the craft at fixed control centres together with a selective communication system for air–ground communication.

(*c*) Collision prevention, which requires an airborne (shipborne) means of determining the position or neighbouring craft.

The transmitters and receivers with modulation and measuring facilities and indicating instruments are still under development. A test installation for position fixing has been set up in the Paris area.

2. DESCRIPTION OF OPERATION [1–14]

2.1. *The Equiphase Lines*

The moving hyperbola branches called equiphase lines are characteristic of the Radio Mesh System. They are created by two transmitting stations A and B located at a distance d, which are modulated with certain low frequencies p and q, in a sinusoidal manner or with pulses. The times of simultaneous reception of these signals are measured. The values of the low frequencies p and q, with p being greater than q, are dependent upon the area to be covered by the system. For a test installation, which will be discussed in section 2.4, $p = 385$ c/s for transmitter A, and $q = 384$ c/s for transmitter B. The creation of the equiphase lines shall be described in detail below. The mathematics are treated in refs. 1 and 9. In Fig. 1 the two transmitting stations are located in A and B At a moment t_o a pulse shall be transmitted by both transmitters simultaneously. These two pulses can be received in coincidence in locations situated on the

* " God has called Mr. Pierre Guadillère away from this earthly life on 13th April, 1960."

median perpendicular of the line connecting A and B. The next pulse is emitted by the transmitter A after an interval of $1/p$ has elapsed, and by transmitter B after an interval of $1/q$ has elapsed. Hence, the pulse is emitted by transmitter B later by an interval of

$$\Delta t = 1/q - 1/p = (p - q)/p \cdot q$$

During the time Δt the pulse emitted by the transmitter A has travelled already the distance $2e = c \cdot \Delta t = c(p - q)/p \cdot q$ where c is the velocity of

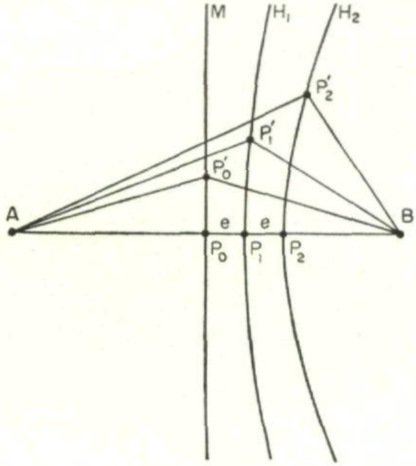


Fig. 1. Formation of isophases

electromagnetic waves. The two pulses meet in the point P_1 on the line AB. The distance of P_1 to the transmitting station A is greater by $2e$ than to the transmitting station B. The distance $P_0 - P_1$ then equals e. Like for the line of connection A–B it is true for all points with coincidence of the second pair of pulses that the difference of their distances to A and B always equals $2e$. Hence, these points (P_1) are located on the hyperbola branch H_1 with A and B as foci. In the next pair of pulses emitted by the transmitting stations A and B, the pulse from B is delayed by the time $2\Delta t$ against the pulse from the transmitting station A. Therefore, the difference of the distances from A and B to the points of coincidence becomes $4e$. These points, hence, are located on the hyperbola branch H_2 and the distance P_1–P_2 again equals e. By the transmission of pulses by the transmitter A with a recurrence frequency of p, and by transmitter B with a recurrence frequency of q, discrete hyperbola branches are produced with A and B as foci, which move in steps from A toward B and whose shape is changed in accordance with a hyperbola pattern. The distances of the intersection of the hyperbola branches (equiphase lines) with the line AB, i.e. the steps of their movement are

$$e = c\frac{p - q}{2p \cdot q}.$$

With $p = 385$ c/s, and $q = 384$ c/s,

$$e = 3 \times 10^5 \frac{385 - 384}{2 \times 385 \times 384} = 1.02 \text{ km}$$

After the period of $T = 1/(p - q)$ the passage of the equiphase lines is repeated. With the values of 385 c/s and 384 c/s a point in the area extending between A and B is scanned by the moving equiphase lines in intervals of 1 sec.

If the modulation of the transmissions of A and B is of the sinusoidal type, the zero passages of the sine curves are used for establishing coincidence in the receiving equipment of the craft. In this manner hyperbola branches* are created which move in a constant manner from focus A to focus B (Fig. 2).

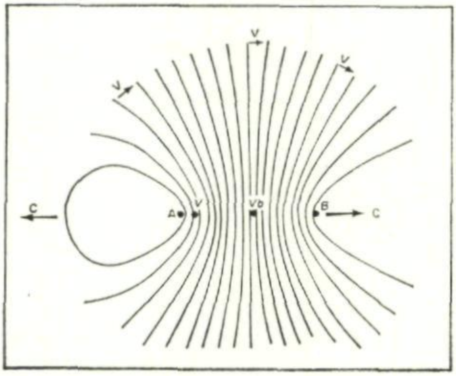


Fig. 2. Movement of the isophases

For determining lines of position and positions by means of equiphase lines, several methods have been suggested by Gaudillère, which will be dealt with in greater detail below. The essential properties of the equiphase lines are as follows:

(*a*) they are hyperbola branches with the transmitting stations A and B located in the foci;

(*b*) their velocity along the line AB is

$$V_0 = c\frac{p-q}{p+q}$$

and is substantially slower than the velocity of electromagnetic waves c. Beyond the connecting line the velocity of movement $V \approx V_0/\sin\theta$, where 2θ is the angle between the connecting lines of the position established and the transmitting stations A and B;

(*c*) a point in space is scanned at the frequency $F = p - q$ (" scanning frequency ") or within the period of $T=1/F=1/(p-q)$ (" scanning period ");

(*d*) only the distance d of the transmitting stations is smaller than $c/(p+q)$ of $V_0 \,.\, T$, there will be one single equiphase line present in space. Location is then unambiguous;

* The exact name is " Oval of Descartes ", but for practical purposes they may be assumed to be hyperbolae, since p and q are only slightly different.

(*e*) when the transmissions are provided with square or pulse modulation, the equiphase lines move in steps. The distance of the hyperbola branches on the base line AB then is

$$e = c\frac{p - q}{2pq} = V_0 \frac{q + q}{2pq}$$

The interference pattern is determined by the location of the transmitting stations and the selection of the modulation frequencies p and q, which are within the audio frequency band, e.g. 385 c/s and 384 c/s as used by the experimental network set up in the Paris area. Then $T = 1$ sec and $V_0 = 390$ km/sec. The maximum distance d of the transmitters A and B required for unambiguous position fixing is $d = T \,.\, V_0 = 390$ km. When pulse modulation is employed, the equiphase lines move from A toward B in a maximum of 385 steps. The distance e of two consecutive hyperbola branches is approximately 1 km.

For transmitting the audio frequencies p and q, any type of modulation may be selected. However, square or pulse modulation offer the advantage that in the airborne receiver an exact measurement of the time of passage of the equiphase lines can be performed on the steep rising edge, i.e. the time of coincidence of the signals received from the transmitting stations A and B can be determined accurately. The frequencies of the radio-frequency carrier are dependent upon the area to be covered. It must be borne in mind, however, that multiple-path propagation such as interference between ground waves and sky waves makes it difficult to determine the time of passage of the equiphase lines and thus impairs the accuracy of time measurement and, hence, the accuracy of location. The moving equiphase lines can be used for position fixing on board by one of the following two methods.

2.2. *Method of Location by " Simple Equiphase Lines "*

In the area extending between the transmitting stations A and B the equiphase lines move at the velocity V and at a time interval of T. When the equiphase line passes through the location of a third transmitting station set up in the vicinity of A or B, a signal S is triggered on an additional carrier frequency. The transmissions of the transmitting stations A, B and S are received by the airborne receiver and the time difference is determined between arrival of signal S and passage of the equiphase line, i.e. that moment when signals transmitted from the transmitters A and B are in coincidence. Thus a hyperbolic line of position is established. A second hyperbola system is created by a second chain of transmitting stations, and can be determined on board. The intersection of both lines of position is the fix using two intersecting hyperbola systems. The transmitting station S may be common to several hyperbola systems.

2.3. *Method of Location by " Conjugated Equiphase Lines "*

The method of location by " conjugated equiphase lines " (Fig. 3) is more interesting than the creation of the hyperbola system by the method of simple equiphase lines. Four transmitting stations are required for this

method, which are installed at the corners of the service area, e.g. of square or rectangular shape with the corners A, B, C, D. The transmitting stations A and C located on the end points of one of the diagonals are modulated with the frequency p, and the transmitting stations B and D located on the end points of the other diagonal are modulated with the frequency q. In this manner four equiphase lines are created between the transmitting stations with the transmitters being located in the foci. Since the frequency

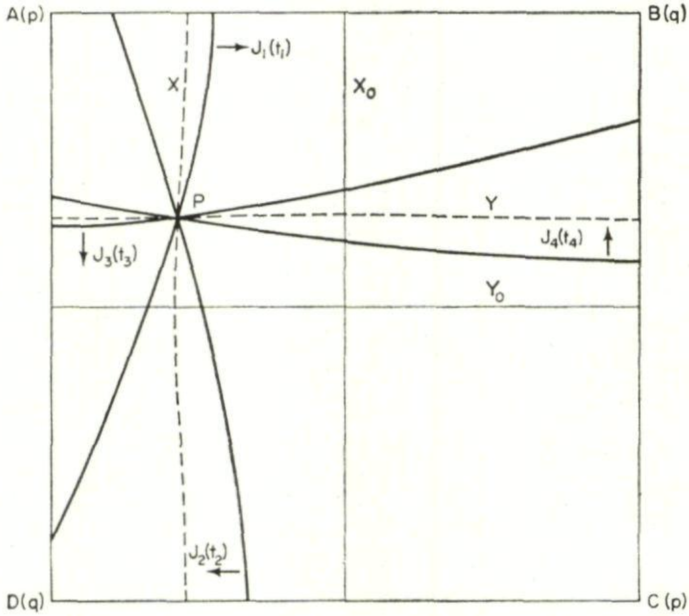
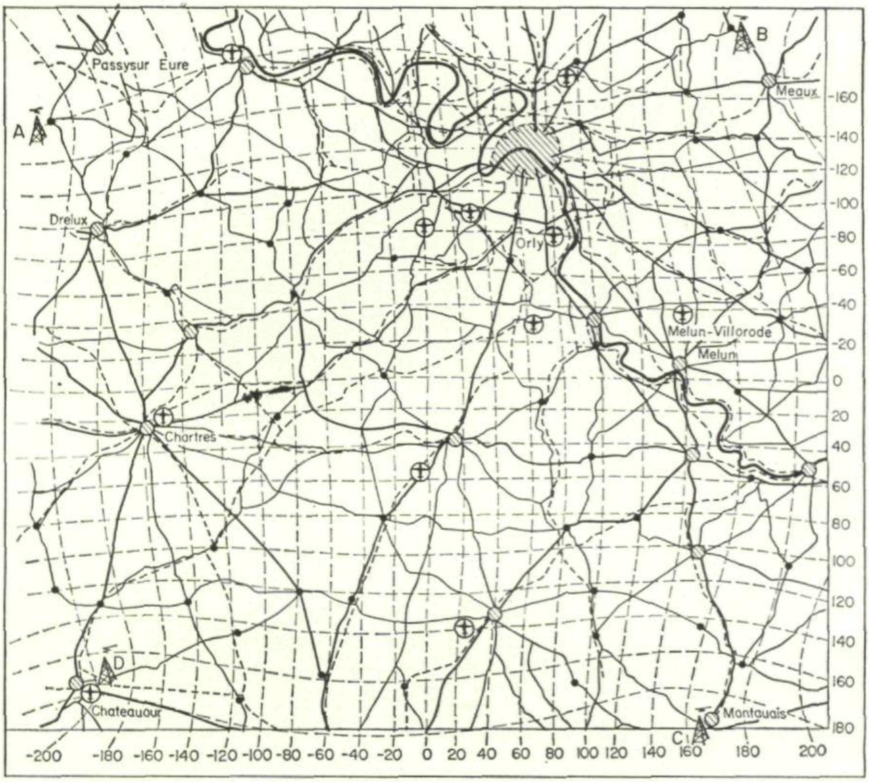


Fig. 3. Method of " conjugated " isophases

p is greater than the frequency q, one equiphase line J_1 moves from A toward B, and a second equiphase line J_2 moves in the opposite direction from C toward B. On board the aircraft the times t_1 and t_2 of passage of the two equiphase lines J_1 and J_2 are measured, and the difference $t_1 - t_2$ supplies a line of position X which is approximately parallel to the side AD. A similar measurement is performed on the equiphase lines J_3 and J_4 from A to D and from C to B. Thus a line of position Y is obtained, which is approximately parallel to the other side AB of the square. The lines of position X and Y form an approximately rectangular grid system within the useful service area of the system, which is determined by the square ABCD. The edges of the grid are slightly distorted and are hardly useful for location purposes outside the square. The network of X and Y coordinates of the experimental installation in the Paris area is shown on Fig. 4. The distortions towards the edges shall be reduced by additional measures. The modulation frequencies p or q respectively of the transmitting stations A and C or B and D respectively must be stabilized and synchronized, since the frequencies and phases of the modulation determine the speed of

movement of the equiphase lines and their position in space. When the squares are arranged adjacent to each other in order to enlarge the service area, a single transmitting station may be used for one corner of the four adjacent squares. In such a case only one transmitting station for each square is required with the exception of the fringe areas of the service area.



Transmitter.
Airport.
Railway line.
Road.

Fig. 4. Demonstration of " Radio Web " System.
Remark: Numbers given to the lines of position north–south (x-lines) and east–west (y-lines) refer to 1/1000 *of a second.*
Scale: 1 : 1.000 000

Figure 5 illustrates the network of X and Y coordinates covering the North Atlantic and the transmitting stations arranged at the corners of a rectangle. Transmitters of high power would be needed. Besides, a method of synchronizing the Master and Slave stations still has to be developed which would be suitable for ranges of approximately 3500 km.

The signals of the four ground transmitting stations are received by four

receivers. The points in time t_1 to t_4 of the passage of the four equiphase lines J_1 to J_4 are determined by coincidence detectors. Electronic time measuring facilities determine the time differences $x = t_1 - t_2$ and $y = t_3 - t_4$ and indicate the numerical values of the corresponding lines of position X and Y or control a route tracer which indicates the position of the craft on a chart that is only slightly distorted. For determining the time differences x and y, two methods have been developed:[11,12]

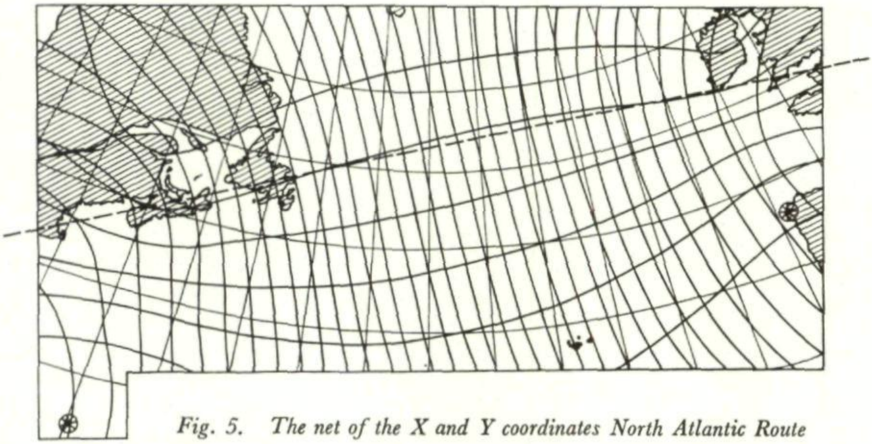


Fig. 5. The net of the X and Y coordinates North Atlantic Route

(*a*) A dual electronic counter is fed by a 1000 c/s oscillator. The coordinate X is provided by the number of microseconds between the passages of the equiphase lines moving at the speed V.

(*b*) A second type of indicator measures directly the time interval between the arrival of the signals emitted by the transmitting stations A and C or B and D respectively. The pulses travel at the velocity of electromagnetic waves. Without any change in the transmission system, fixed hyperbola systems are observed with the transmitters located as foci at the end points of the diagonals. The indicator then calculates the sum of these two values and the difference between them in order to obtain the lines of position X and Y. More detailed information of this method of measurement has not yet been published.[12]

2.4. *The Experimental Network near Paris*

An experimental network has been set up in the Paris area. It consists of four transmitters located at the corners of a quadrilateral, the sides of which are approximately 100 km in length. These transmitters have a rated power of 100W. The carrier frequencies are selected around 2 Mc/s. The Master transmitters A and B are modulated in square signal to the frequency of $p = 385$ c/s or $q = 384$ c/s, respectively. The modulations are established by crystal stabilized oscillators. These transmissions are picked up in the vicinity of the Slave transmitters C and D, which are modulated

by a local oscillator synchronized on the signals of the transmitters A and B. The airborne equipment consists of four receivers which are tuned to the four ground transmitting stations.

The outputs of the receivers are applied to the coincidence detectors and to the time measuring facilities which supply the coordinates X and Y. These coordinates form an approximately rectangular system of coordinates as illustrated on Fig. 4. Flight tests were made during which the signal levels temporarily fell below 10 mV/m. Therefore the measurements were impaired by noise and interference. Under these conditions the greatest errors of position fixing never exceeded 2 n.m. It is expected that the accuracy can be increased substantially by more powerful transmitters. Then the distance between the transmitting stations also could be increased since the indication remains unambiguous up to a distance of 390 km with the modulation frequencies $p = 385$ c/s and $q = 384$ c/s.

2.5. *Traffic Control*

The utilization of the moving equiphase lines may become of particular importance for position reporting of aircraft to stationary control centres. On passing over an aircraft the equiphase line, e.g. J_4, which moves from C to B, causes transmission of two v.h.f. pulses by an airborne transmitter. This signal is then picked up the the control centre. The first pulse is triggered after passage of the equiphase line with a time lag proportional to X, which is the distance of a position to the line connecting B with C, and the second pulse is triggered with twice this time lag. The reason for the delay of the transmitted pulses is the speed of travel of the small areas on the hyperbolic channels being greater than the propagation speed of the wave [9,13,14]. In this system the position is fixed in a system of coordinates with hyperbolae and X-values (Fig. 6).

The signal is received at the control centre and, for example, illuminates the spot of a cathode-ray tube. The tracer beam is moved in compliance with the equiphase line J_4 by local control facility. Thus a true image of the movement in space of the equiphase line J_4 is obtained. At first the dark tracer beam moves in steps from point C to point B on the display. When the first signal from a craft is received, the beam is deflected on a hyperbola branch which corresponds to the instantaneous position of the equiphase line. When the second signal is received the tracer beam is illuminated. During this interval it has reached the position of the craft on the hyperbola. Within the scanning period T, e.g. 1 sec, the positions of all craft present in the given area ABCD shall be indicated so that continuous surveillance would be possible.

When several craft are located simultaneously on a hyperbola branch of the equiphase line, difficulties may arise due to the different propagation times of the signals travelling from the craft to the control centre. Therefore the signals of the individual craft cannot be identified reliably. For this reason additional measures have been suggested, for instance delaying the transmission of the signal on board corresponding to the position of the craft on the hyperbola branch. Furthermore it is intended to transmit the altitude by coding the signal with the altitude as determined by the altimeter. This would allow indication of position and altitude at the fixed control centres.

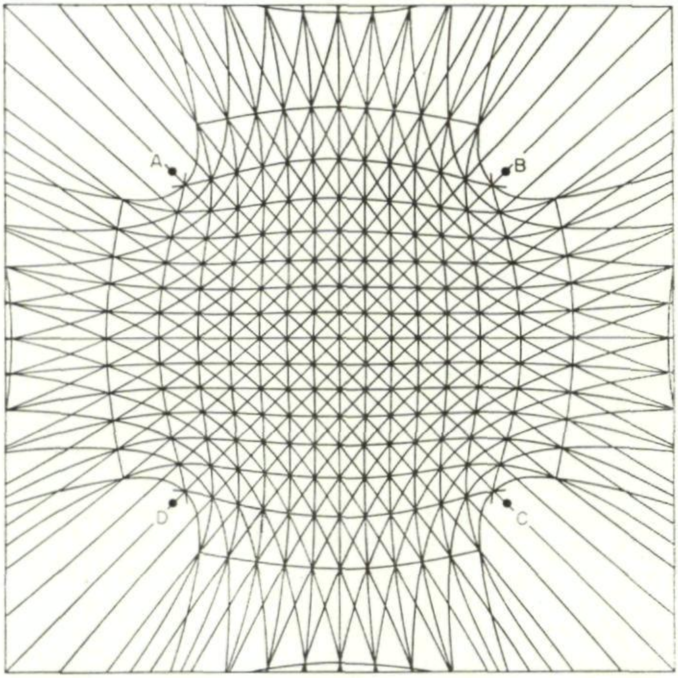


Fig. 6. Formation of Map square coordinates with diagonale hyperboles

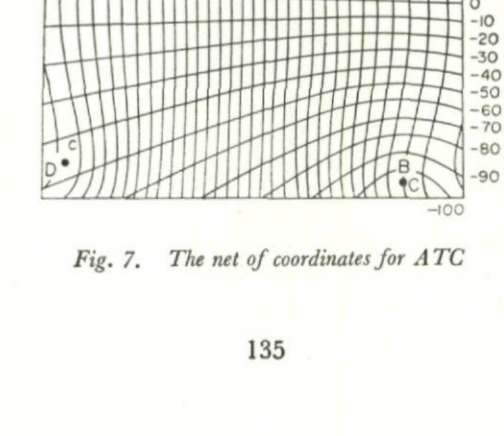


Fig. 7. The net of coordinates for ATC

For selective communication between the control centre and the respective craft, a mark shall be adjusted manually on the luminous spot on the cathode-ray tube representing the aircraft. A pulse on another radio-frequency carrier shall be transmitted at such a moment by the ground station that the pulse is received on the aircraft exactly when a signal is emitted by the airborne transmitter. This measure is intended to eliminate blocking a normal traffic receiver for air–ground communication. Thus communication would be possible between the control centre and the respective craft without the knowledge of crews of other craft equipped with the same receivers.

Equipment for traffic control and selective contact are still being developed. Therefore no information on their operational properties is available.

2.6. *Collision Prevention*

Since the positions of the craft are displayed, it should be possible to transmit to the craft a collision warning message. For this purpose, the positions of nearby craft will have to be transmitted by the ground station and displayed on a cathode-ray tube on board the craft with the own craft located in the centre. It has also been suggested that the craft pick up directly the position signals transmitted by nearby craft. Aircraft crews are primarily interested in being warned of other aircraft flying on adjacent altitudes. If the signals containing position and altitude information are coded according to the altitude, they may be filtered in order to accept only those from altitudes adjacent to the altitudes of the aircraft involved. Future developments will show whether these suggestions with regard to collision prevention are acceptable to shipping and aviation.

3. ACCURACY AND RANGE (COVERAGE)

Since the Radio Mesh System is still in the development stage, no data are available on ranges and accuracies obtained except for the experimental network set up in the Paris area. When the method of conjugated equiphase lines is employed, frequencies and transmitter powers chosen must be such that sufficient field strength is available within the service area covered by the four transmitters. The accuracy of the Paris installation[5] is claimed to be 2 n.m. However, it is capable of being improved by using more powerful transmitters. The results obtained from a new trial installation were very satisfactory. The accuracy of fix was approx. $\pm$ 1 km[13] at all tests. For covering the area of the U.S.A., 15 transmitting stations of 100 kW each would be required.[11] Four transmitters should be located at the corners of each quadrilateral, the sides of which would measure approximately 600 n.m. The transmissions should be modulated to frequencies of $p = 155.1$ c/s and $q = 155.0$ c/s. The scanning period then would be 10 sec.

For long-range navigation, e.g. over the North Atlantic, modulation frequencies of approximately 60 c/s and carrier frequencies of 90–110 kc/s or 10–14 kc/s have been suggested.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

In position fixing the grid square determined by the radio coordinates shall be indicated on board by the X and Y values. Also a route tracer is

provided. Since the positional data are received at 1 or 10 sec intervals, connection to the automatic flight control system is hardly possible. No sufficient information on traffic control and collision prevention applications is available.

5. GROUND STATIONS AND AIRBORNE (SHIPBORNE) EQUIPMENT

The ground station equipment required is dependent upon the desired range and on the frequencies and power required accordingly. It is said to be of the same order of magnitude as for other radio navigation systems.[11,12]

6. CONCLUDING REMARKS

The Radio Mesh System offers interesting possibilities by the combination of position indication with traffic control and by the use of moving equiphase lines. However, no statements can be made with regard to accuracy, reliability and the extent of ground and airborne equipment required prior to conclusion of the laboratory work and subsequent trials.[13] In a paper read by Gaudillère at the Berlin conference, held in 1958, by the Ausschuss für Funkortung,[8] he mentioned a period of 2–3 years as necessary for completion of the work. No information is available on the work performed in the U.S.A. by Stavid Engineering Inc.

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2.13. DELRAC

(DEcca Long Range Area Coverage)

and

OMEGA

H. Lueg

1. GENERAL INTRODUCTION

DELRAC and Omega are hyperbolic radio navigation systems, which are similar in many respects. Both systems operating in the band 10–14 kc/s have been designed to provide position fixing coverage on a world-wide basis. Phase comparison of c.w. signals from two stations enables the determination of a line of position. Both systems are only in the planning stage, but relatively accurate data have been obtained from preliminary tests carried out with the proposed frequency band. Such data constitute the basis for the design work on DELRAC carried out at present, whereas nothing is known of any projects of design on Omega.

Both systems employ time-multiplex and frequency-multiplex techniques. For DELRAC, the arrangement proved with DECTRA (Chapter 2.09) is proposed. For Omega it is only known that the indication by various instruments of the phase differences is proposed.

The DELRAC system has been proposed by the Decca Navigator Co., London.[1] It is based on well-established Decca (Chapter 2.08) and DECTRA (Chapter 2.09) techniques. It is estimated that twelve pairs of stations would provide coverage over the entire surface of the earth with a fix accuracy everywhere better than 18 km at the 95 per cent probability level. Ambiguity can be reduced to an extent by producing coarse patterns in a suitable manner.

The Omega system[2] is the outgrowth of the development of a modulation-phase measurement navigation system with a 200 c/s modulation on a 40 kc/s carrier. The base line between two ground stations was approximately 3500 km. This system has had five years of operation. The system accuracy measured was $\pm$ 7.5 km at 90 per cent probability. In 1950 it was decided to add a c.w. frequency of 10 kc/s to the 40 kc/s frequency modulated with 200 c/s. It was intended to resolve the ambiguity of the 10 kc/s hyperbolic line by means of the 200 c/s modulation. One year of tests have indicated that the absolute accuracy of the 10 kc/s portion of the system is better than 1 n.m. throughout the coverage area. This amazing accuracy was the reason for commencing further studies in 1956 on the propagation over long ranges. These studies indicated that a system, which uses two adjacent frequencies in the 10–14 kc/s range for producing the radio coordinate, probably could secure a world-wide coverage at an accuracy of only $\pm$ 1 n.m. at 95 per cent probability. Tests for determining

the most favourable frequency distance between the two transmitted frequencies, which is needed for lane identification, are in progress. Test results enabling a final assessment are not yet available. It is estimated that a world-wide coverage could be obtained with six ground stations.

2. SYSTEM DESCRIPTION

2.1. *The DELRAC System*

The DELRAC system is a hyperbolic system of navigation. A hyperbolic pattern is obtained of phase-locked frequencies transmitted from a pair of transmitting stations A and B, which are located on a base line 1400–2000 km

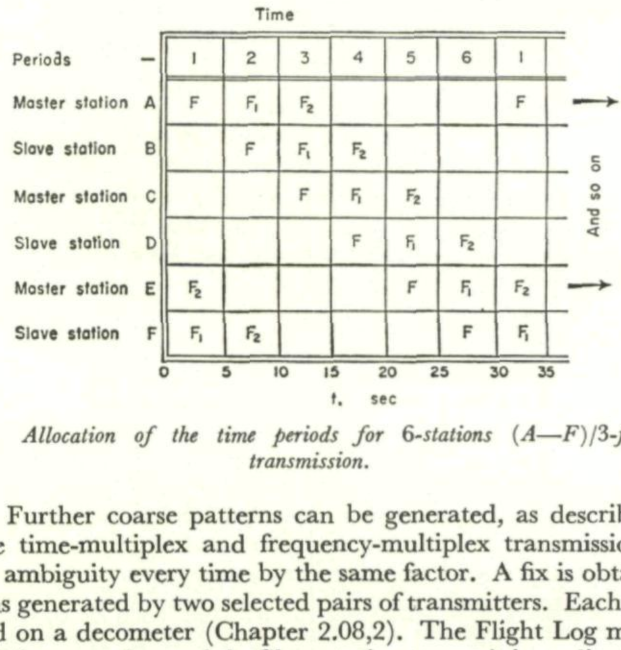


Fig. 1. Allocation of the time periods for 6-*stations* $(A—F)/3$-*frequency transmission.*

in length. Further coarse patterns can be generated, as described below, by suitable time-multiplex and frequency-multiplex transmissions, which reduce the ambiguity every time by the same factor. A fix is obtained from the patterns generated by two selected pairs of transmitters. Each hyperbola is indicated on a decometer (Chapter 2.08,2). The Flight Log may also be used. The Master station and the Slave station transmit in cyclic alternations groups of signals (transmission of a carrier for a period ranging from 10 msec to 1 min). Let us assume F be the lowest frequency transmitted (between 10 and 12 kc/s). A signal on the frequency F transmitted from the Master station (Fig. 1) is subsequently followed by a signal on the same frequency transmitted from the Slave station. By continuously operating oscillators located in the Slave station, a phase-locked transmission is secured. Hence, there the instantaneous phase relation at the beginning of the transmission is equal to the phase relation of the signal received from the Master station.

After the Master station has transmitted the frequency F for a period of 5 sec, it changes over to $F_1 = F(1 + 1/n)$. At the same time, the Slave station begins to transmit for the next 5 sec the phase-locked frequency F. After these 5 sec have elapsed, the Slave station takes over the phase-locked transmission of F_1, while the Master station changes over to $F_2 = F(1 + 1/n^2)$. Then the Master station interrupts its transmission, while the Slave

station continues to transmit for 5 sec the frequency F_2. Now, both transmitters close down for a period of 3×5 sec thus concluding the cycle. Then the Master station begins transmitting again the frequency F. The allocation of time periods for the frequencies F, F_1 and F_2 of the pair of transmitting stations A, B is illustrated by the first two lines of Fig. 1.

The number n, which is always an integer, is known as the admissible measure of ambiguity of two hyperbolic patterns; its magnitude shall not normally become greater than 3. The ambiguity of a fine (or highly

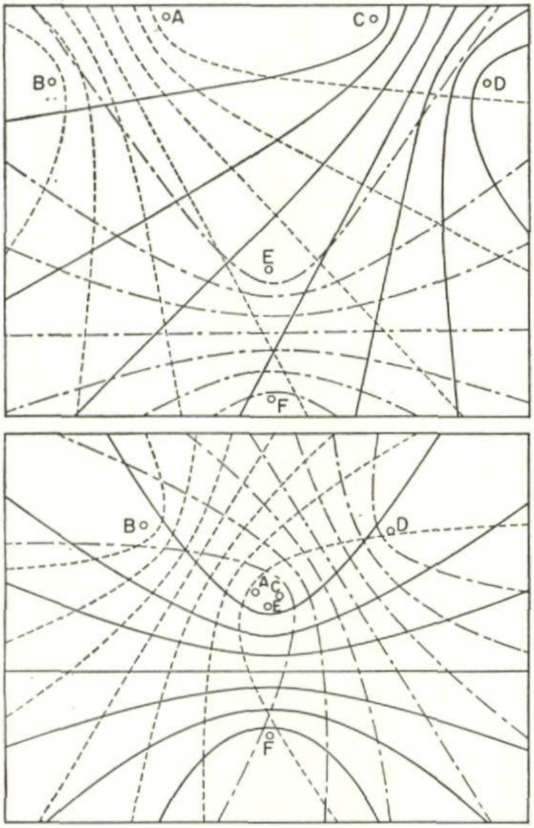


Fig. 2. Arrangement of three pairs of transmitting stations which, according to their location, provides fixes of different accuracy.

accurate) hyperbolic pattern should be eliminated in steps by coarse and coarser patterns. The DELRAC system uses the frequencies F_1, F_2, $F_3, \ldots$ in a manner different from Decca. Let us assume $F = 10$ kc/s, then, if $n = 3$, the frequency $F_1 = F(1 + 1/n) = 13\frac{1}{3}$ kc/s, $F_2 = 11\frac{1}{9}$ kc/s, and $F_3 = 10\frac{1}{2}$ kc/s. All frequencies transmitted from a Master station are synchronized by the common subharmonic F/n^3.

When three pairs of ground stations are used, whose coverage area is different according to their location (Fig. 2), the frequencies F, F_1 and F_2

may be transmitted in compliance with the time schedule represented in Fig. 1.

The operation of the DELRAC airborne receiver is shown on the block diagram Fig. 3. The frequencies F transmitted sequentially in the time periods 1 and 2 from the transmitting stations are fed to two permanently operating oscillators 'A' and 'B' after they have been passed through r.f. amplifiers for phase and frequency control. The phase difference is measured by the F-discriminator and is indicated by a decometer. This indication represents the line of position within a fine hyperbolic pattern.

The 'A' and 'B' oscillator outputs are also fed to frequency dividers and to mixers. During the time period 2, the frequency F_1 is mixed by the mixer with the signal from the same transmitter stored by the oscillator 'A'. The phase relationship of the mixed frequency $F_1 - F = F/n$ in the receiver is the same as if the frequencies F_1 and F were transmitted *simultaneously* from A. The frequency division is ambiguous by the factor n. But one of the n phase relations possible of F/n *always* coincides with the frequency derived by mixing, if the frequencies F_1 and F are propagated at equal velocity. This coincidence for $n = 3$ can be adjusted automatically by a servo mechanism; coincidence always can be re-established even after transmission of reception had been interrupted. The frequency F/n derived from the transmitter A can be phase-compared in a like manner with the frequency F/n derived from the transmitter B. The phase difference measured is the line of position within a F/n hyperbolic pattern. In this way a fix that is coarser by the factor n compared with the F hyperbolic pattern is obtained.

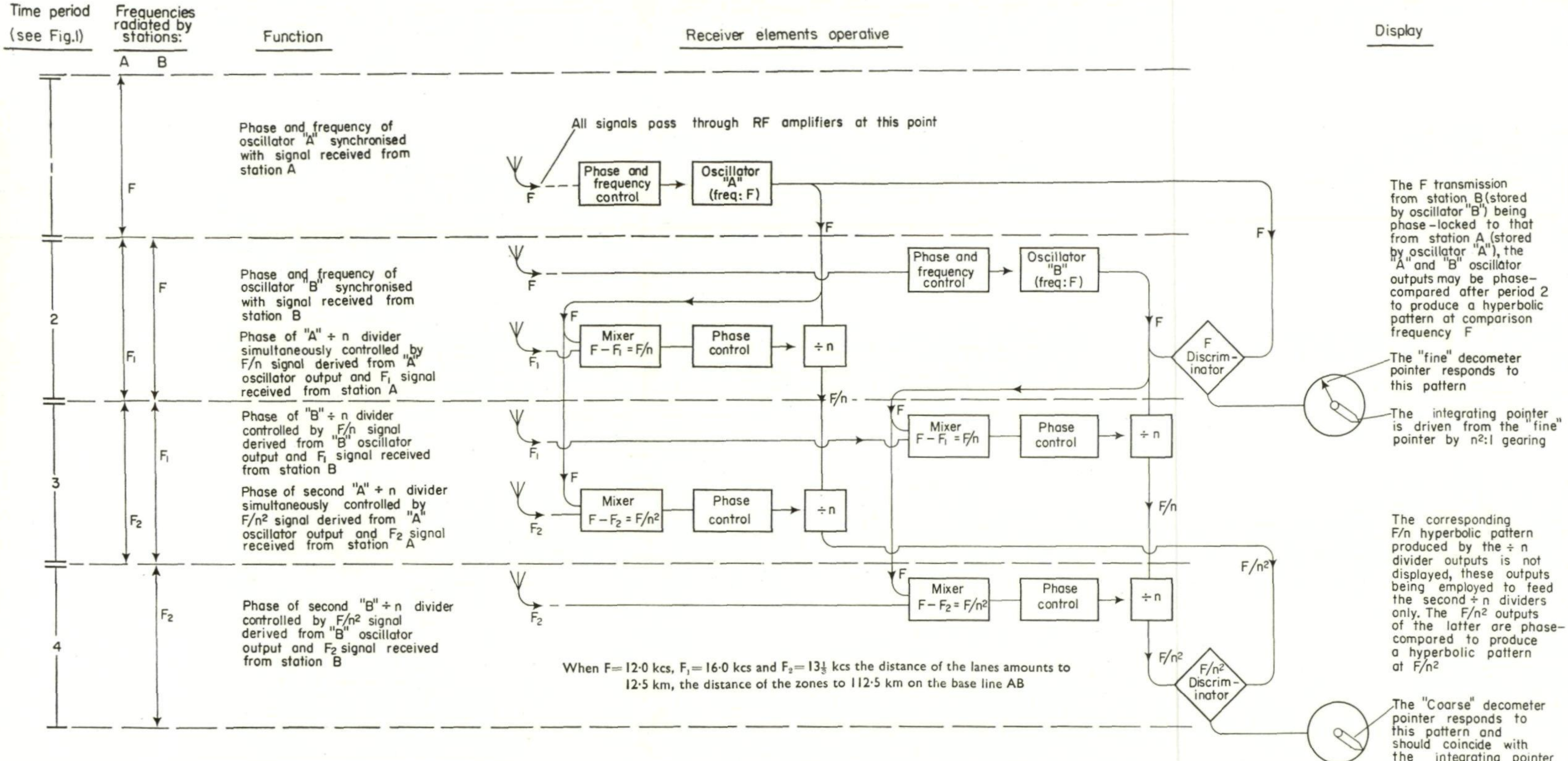
By mixing F_2 with F, the common subharmonic F/n^2 is obtained, which in turn is used for phase control of the divider A/n^2 base upon A/n. Thus a phase comparison is possible of the frequencies F/n^2 derived from the transmitters A and B. The phase difference measured represents the line of position within the still coarser F/n^2 hyperbolic pattern.

This process can be continued: By means of further mixers and dividers and by the use of the frequency $F_3 = F(1 + 1/n^3)$ a F/n^3 hyperbolic pattern is generated, whose hyperbolae are disposed at a distance from each other which is 27 times ($n = 3$) greater than that between the hyperbolae of the fine pattern. In Fig. 3 only the decometers for the F and F/n^2 hyperbolic patterns are illustrated.

The method of synchronization of the change-over function of the ground stations required at 5 sec intervals, and of all receivers in operation required at 30 sec intervals, is not described in detail. But such synchronization can be obtained by transmissions of different duration *without* an additional signalling frequency (similar to DECTRA, Chapter 2.09, Fig. 2).

2.2. *The Omega System*

The time-multiplex and frequency-multiplex system of Omega provides only for one coarse fixing step. The frequency schedule of six stations distributed suitably over the globe and disposed at a distance of approximately 10,000 km from each other, is shown on Fig. 4. Each transmission which is used for a phase measurement, is 1 sec in duration. The transmission of the frequencies F_1 and F_2, which are selected so that they can



Typical carrier frequency allocation (Assuming n = 3)

	F	=	12 kc/s
F_1 =	$F(1 + 1/n)$	=	16 kc/s
F_2 =	$F(1 + 1/n^2)$	=	13·1/3rd kc/s

Hyperbolic position – line patterns (With F = 12 kc/s)

Pattern	Comparison frequency	Lane width on baseline
"Fine"	12 kc/s	12·5 kilometres (13·670 yd)
"Coarse"	1·1/3rd kc/s	112·5 kilometres (69·90 st. miles)

Fig. 3. Simplified block diagram showing how fine and coarse hyperbolic patterns are derived from a pair of Transmitting Stations.

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also in phase. Thus, fading is rarely expected at this point most critical in wave propagation.

(*b*) Beyond the first interference zone, the wave is propagated between the surface of the earth and the ionosphere. The phase variation as dependent upon the height of the *E*-layer is insignificant and considerably less than with higher frequencies.

3. ACCURACY AND RANGE[3]

3.1. *DELRAC*

The range obtainable at any time of the day from a DELRAC ground station transmitting a power of 5 kW and by means of a DELRAC receiver having a 5 c/s pass-band and provided with screened anti-static aerial (cf. description of the Decca system, Chapter 2.08.2) is not less than 5500 km even in conditions of severe interference. The estimated error at the most unfavourable part of the coverage is less than 10 n.m. at 95 per cent probability.

3.2. *Omega*

Six Omega ground stations (but 10 should be used) transmitting 100 kW each could provide world-wide coverage. The estimated error is better than 1 n.m. (95 per cent probability) throughout the coverage area at any time of the day. This error is claimed to have been proved by numerous measurements.[2]

3.3. *Both Systems*

Nothing is known of the method of synchronizing the Master and Slave stations. If the Slave station is synchronized by transmissions from the Master station, variations in the synchronizations are bound to occur due to variations in the propagation. It is not known to which extent the error could be reduced, if both ground stations were synchronized independently of each other, for instance, by atomic clocks. It is not clear why the errors of two closely related systems should deviate so greatly (1 : 10).

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS[3]

DELRAC and Omega can accommodate an unlimited number of users at sea, land or air, and, sufficient field strength provided, under water. Since it is intended to display the DELRAC positions on the Flight Log, manipulation will be restricted to switching on, monitoring, observation of the Flight Log and chart changing. The systematic variations of the *E*-layer can be taken into account by hyperbolic charts incorporating the respective diurnal and seasonal correction factors.

No airborne use equipment has been designed for Omega. Indications of malfunction can be provided on both systems.

5. COST OF THE EQUIPMENT

Twelve pairs of DELRAC stations would provide coverage over the entire surface of the earth. The cost of a complete pair of transmitters is estimated at approximately 4 million DM. The airborne equipment is estimated at 40 kg, the cost is estimated at 32,000 DM.

be synchronized by a common subharmonic, is similar to DELRAC (as far as the phase relation is concerned).

For instance, a receiver which is to determine a line of position within the hyperbolic pattern AB between the fifth and the sixth second (Fig. 4), shall be tuned so that an oscillator $-F_1$ is synchronized by the wave from the transmitter $A - F_1$ (A) and also a second oscillator F_2 (B). No signals are

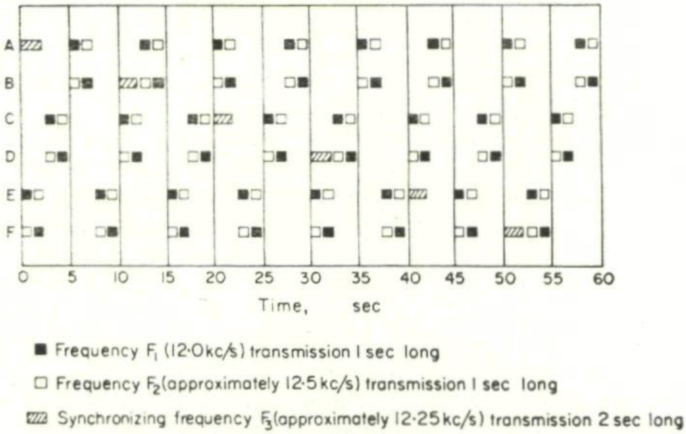

Fig. 4. Transmissions are always interrupted for ¼ sec after two transmissions of 1 *sec each. Allocation of time periods for* 6 *stations* (A/F) 3 . . . *-frequency transmissions* F_1 *and* F_2 *used for fixing and one frequency* F_3 *for synchronizing the changeover function.*

transmitted from second 6 to second 6.25, and the receiver is changed over automatically so that two other oscillators F'_2 (A) and F'_1 (B) are synchronized. Subsequently, the phase difference between F_1 and F'_1 or F_2 and F'_2 respectively is determined, whose value represents the line of position within a F_1 or F_2 hyperbolic lane respectively. With $F_1 = 12$ kc/s, the lane width $(\lambda/2)$ on the base line is approximately 12.5 km. Hence, 800 lanes of this width would be available with a 10,000 km base line.

As in the case of DELRAC, the difference frequency $F_2 - F_1 = 500$ c/s can be derived by mixing in the receiver. A coarse fix can be established within the respective hyperbolic pattern, for instance, between the ground stations A and B. Twenty-four lanes of the frequency F_1 or 25 lanes of the frequency F_2 respectively would be located within a coarse lane.

In order to obtain change-over at the correct moment of all Omega receivers in operation, clocks can be provided which are synchronized by the transmission of a frequency F_3. These F_3 transmissions are 2 sec in duration. However, details are not available.

The reasons for the frequency range chosen, problems of propagation. The frequency range of 10–12 kc/s is most suitable for a navigational aid with world-wide coverage. For the two propagation requirements are satisfied:

(*a*) With increased distance to the transmitter, the sky wave portion is increased and the ground wave portion is reduced gradually. At such distances, where both components have the same intensity, they are

An Omega ground station designed for radiating a power of 100 kW would require a four-tower aerial system with three of the towers at the corners of a 500 m equilateral triangle and the fourth in the middle of the triangle. Each tower would be about 195 m high and their tops would be connected by cable to improve top loading. An 0.5 km diameter circular ground system would be required. The cost of a complete ground station is estimated at 12,000,000 DM, the cost for a shipborne receiver is estimated at 16,000 DM.

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2.14. NAVARHO-H

T. v. HAUTEVILLE

1. INTRODUCTION

As STATED in the system description of Chapter 2.07, one of the main problems in the practical application of Navarho is the difficulty of providing sufficiently stable airborne frequency standards for the distance measurement (10^{-9} within 12 hr).

If a Navarho ground network existed that allowed in any location the reception of two stations—the 30-station network needed for world-wide coverage would meet this requirement—it would be possible to obtain a position fix:

(*a*) from the intersection of two radial lines of position (Navaglobe system, Chapter 2.03);

(*b*) by measuring the bearing to one station and the difference between the distances of both stations. Thus the position fix is determined by the intersection of a radial and a hyperbolic line of position.

Method (*b*) has the designation " Navarho–H " and was proposed to the ICAO by the U.S.A. in 1957.[3] To date nothing is known concerning the state of development or about any tests.

2. SYSTEM DESCRIPTION

Navarho–H is a radio location method by which the position fix is determined by the intersection of a radial and a hyperbolic line of position. Additionally it was proposed to convert, by a computer, the distance difference between the two stations into the distance of the station for which the bearing is measured, thus providing the same type of indication as the original Navarho, that is to give bearing and distance information referred only to one ground station.

Regarding the determination of the bearing see Chapter 2.07.

In order to measure the difference between the distances of the two ground stations a second receiver is required for reception of the signal from the second ground station.

The modulation resp. two carrier transmission of the ground station as mentioned in the Navarho description serves for an approximate determination of the distance difference (see Chapter 2.07,2.2). It is, of course, necessary to maintain constant phase relation between the 250 c/s signals transmitted by the two ground stations. For 250 c/s measuring frequency the unambiguity (lane width) on the base line is 324 n.m. The variation of the distance difference can also be measured by the carrier phase method (see Chapter 2.07,2.1). In this case the carriers received from the different ground stations are divided down to 1 kc/s. At this frequency the phase measurement is made. The distance difference measured by the carrier phase method is unambiguous for about 0.8 n.m.

3. ACCURACY AND RANGE

3.1. *Accuracy*

It is expected that the following tolerances are not exceeded for 95 per cent of all observations.

bearing	$\pm 1°$
distance	± 3 n.m.

3.2. *Range*

For a network equipped with ground installations providing 100 kW radiated power and within about 2000 n.m. distance max., ranges of 2000 n.m. are expected.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

Because it is planned to convert by computer the distance difference into the distance to the station for which the bearing is measured, the final information supplied by Navarho–H are the Rho and Theta values as in the case of the original Navarho. Thus the practical application and operation will correspond largely to the description as given in Chapter 2.07,4.

5. GROUND AND AIRBORNE EQUIPMENT

5.1. *Ground Station*

Compare the description as given in Chapter 2.07,5.

The same ground stations are used as for Navarho. Additional means are to be provided to maintain a stable phase relation between the carrier resp. modulation frequencies of the various ground stations.

5.2. *Airborne Equipment*

No airborne frequency standard is required. Instead a second receiver is needed other than for the normal Navarho. Further, a computer must be added to convert the distance difference measured into the distance to the ground station for which also the bearing is determined. It is estimated that the complete airborne equipment for Navarho–H will not exceed a volume of 30 l. and a weight of 30 kg.

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2.15. NAVARHO–HH

T. v. HAUTEVILLE

1. INTRODUCTION

THE problem of the airborne frequency standard required for Navarho is avoided by the version Navarho–H, where the difference in distance of two ground stations is measured, thus determining the position fix as the intersection of a radial and a hyperbolic line of position. The next step is obviously to replace the radial by a second hyperbolic line of position and to get the fix from two similar lines of position. This version is designated " Navarho–HH ". For obtaining a fix, three ground stations with stable phase relation are required that can be received simultaneously.

The 30-station network necessary to provide world-wide Navarho coverage (Chapter 2.07,5.1) would not meet this condition, and additional ground stations would have to be installed for Navarho–HH. These additional ground stations need not to be complete Navarho stations. Simple omni-directional transmission installations are sufficient, that only radiate the carrier resp. the two carriers needed for the distance measurement.

2. SYSTEM DESCRIPTION

The position fix supplied by Navarho–HH is given by the intersection of two hyperbolic lines of position. The distance difference is directly indicated in microseconds. For the evaluation a map with superimposed hyperbolic grid is recommended. Concerning the distance measuring method, refer to the system description of Chapter 2.14,2.

3. ACCURACY AND RANGE

It is estimated that at distances up to 1500 n.m. the standard deviation will not exceed 3–5 n.m. for 95 per cent of all observations made.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

Evaluation of the measured data is made by means of a map with superimposed hyperbolic grid. A further consideration is the possibility of a computer that converts the hyperbolic coordinates into a direct reading of geographical longitude and latitude. Such a computer, however, would be rather complicated because of the rather high differences encountered in the distance of the ground stations utilized for measurement.

5. GROUND STATION AND AIRBORNE EQUIPMENT

5.1. *Ground Station*

See system description of Chapter 2.07,5. The same ground stations are used as for Navarho. Additional means are to be provided to maintain a stable relationship between the carriers resp. the modulation of the ground

stations. Auxiliary ground stations radiating only the criteria necessary for distance measurement will cost about 50 per cent of a standard Navarho ground station. Besides that, the site requirements are considerably less stringent, because the radiation pattern has no influence on the measuring accuracy.

5.2. *Airborne Equipment*

The weight and volume of the airborne equipment are estimated as approximately 25 kg and 30 l., respectively.

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2.16. NAVARHO-RHO

T. v. Hauteville

1. INTRODUCTION

Whereas in the case of Navarho (Chapter 2.07) the fix or position is obtained from a radial position line (bearing) and a circular position line (distance), both referred to a ground station, with the version Navarho-Rho the position is determined by two distance measurements referred to two different ground stations. Because the accuracy of the distance measurement is markedly better than the bearing measurement, it is believed that with two distance measurements a considerably higher fixing accuracy will be obtained then with the Navarho system.

2. SYSTEM DESCRIPTION

Navarho-Rho is a radio location system by which the fix is obtained from the intersection of two radial lines of position. Regarding the details of the distance measurements reference is made to the Navarho description in Chapter 2.07.

3. ACCURACY AND RANGE

It is estimated that at a distance of 2000 n.m. the standard deviation will not exceed 3 n.m. if about 100 kW are radiated by the ground station.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The evaluation of the measured distance values can be done by rule and compass on a map presenting true distances. It is also possible to use a computer for converting the distance information into geographical coordinates. Further details on these problems were not given in the published proposals.

5. GROUND STATION AND AIRBORNE EQUIPMENT

5.1. *Ground Stations*

The same ground stations are used as for Navarho. For details refer to the system description of Chapter 2.07,5.

5.2. *Airborne Equipment*

For the airborne equipment, needing a frequency standard, a weight of about 35 kg and a volume of 45 l. are estimated.

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3. ACCURACY AND RANGE OF RADIO NAVIGATION SYSTEMS

G. ULBRICHT

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1. DEFINITION OF THE TERM "POSITIONAL ACCURACY"

POSITIONAL data are useful only if they also contain information about the magnitude of the position error that will not be exceeded at a known probability. Since the accuracy of a navigation system is reduced at increased distance, a useful operating range is defined by the admissible error (or minimum accuracy). The useful operating range is always less than the receiving range of the transmitting station. At short distances to an aid to navigation the admissible errors may be exceeded even at reduced distance. Thus the range also may be limited (minimum distance).

Under these conditions two accuracy limits can be established beyond which no useful fixes can be obtained from a navigation system.

(*a*) The " accuracy of the line of position " (position line accuracy). The true position is located at a distance of less than p nautical miles from the line of position established by measurement; the probability is known.

(*b*) The " positional accuracy ". The true position is located at a distance of less than q nautical miles from the position established by measurement; again, the probability is known.

The following range limits of a system satisfy the requirements of long- and medium-distance navigation:

at a probability of 95 per cent (position) and 98 per cent (line of position)—according to ICAO—

an error of 1, 2, 5 and 10 n.m. in medium-distance navigation systems.*

The admissible error limits define two families of range limit curves of the position. One of these families delineates the area of sufficient positional accuracy, and the other one delineates the area of sufficient position line accuracy. These curves establish the maximum and perhaps the minimum ranges of the aid to navigation—the transmitter.

While the contours of the receiving range of the transmitting stations are circles, the contours of the useful operating range are no circles (except in systems supplying radials and positions on radials).

* For the line of position either a deviation is admissible which is based on a higher degree of probability than is the case with regard to the position, or smaller deviations are admitted (e.g. 70 per cent) at equal probability in order that two lines of position give an admissible accuracy of fix even if their angle of intersection is not exactly 90°.

The possible errors which limit the positional accuracy at maximum range are composed of systematic and accidental errors. The systematic errors can be eliminated by calibration. All errors may occur both in the ground installation and in the airborne (shipborne) equipment.

(*a*) The systematic errors essentially consist of:

(i) equipment errors, which may depend on angle, time and frequency;

(ii) errors which are dependent upon the air speed (e.g. due to the inertia of the indicating instruments, slow speed of rotation of the directivity pattern, etc.);

(iii) errors due to the influence of polarization;

(iv) local short-range influences which may be dependent upon angle, frequency and distance;

(v) errors occurring during propagation which are of the regular kind (reflections on mountains, coast refraction, ground conductivity, tropospheric influences);

(vi) systematic influences of the ionosphere due to tilted reflecting layer.

Most of the systematic errors can be defined for the majority of navigation systems; hence they can be illustrated by calibration curves. Therefore they shall not be considered further in this paper. The errors due to changed ground conductivity, tropospheric influences, errors due to the influence of polarization, and part of the great circle deviations are of a systematic nature; however, they cannot be measured in practice.

It is recommended to take into account such systematic errors which cannot be measured by increasing the parameters of the standard deviations of the following group of the accidental errors. Practice will show the degree to which this method is admissible.

(*b*) After elimination of the systematic errors, the accidental errors should be considered in the investigation of the accuracy. (Accidental errors are such errors which are subject to a distribution according to the Gaussian error function and which can be averaged from a sufficient number of observations.) They comprise:

(i) propagation errors (sky waves);

(ii) errors due to inaccurate adjustment, reading and interpretation, errors due to noise and atmospherics;

(iii) errors due to amplitude and frequency inaccuracies.

2. THE STANDARD DEVIATION AND THE ROOT MEAN SQUARE ERROR

The accidental errors of each system can be determined by observing the standard deviation σ. Perhaps several values of σ will have to be determined if they are independent of each other.

$$\sigma = \sqrt{\left(\frac{\sum_{1}^{n}(a_i - M)^2}{(n-1)}\right)}$$

where $a_1, a_2, \ldots a_i \ldots a_n$ = readings of n observations,

M = arithmetical mean derived from n measurements, and

$(a_i - M)$ = error of a single measurement (deviation).

The value of σ determined directly the probability distribution of the deviation x from a line of position (distribution according to a Gaussian error function)

$$w(x)\,\mathrm{d}x = \frac{e^{-x^2/2\sigma^2}}{\sqrt{(2\pi\sigma^2)}}\,\mathrm{d}x$$

If this probability distribution is known, the magnitude of the probability can be calculated at which an error lies between zero and a pre-determined upper limit. The result of such a calculation is, for instance, that there is a 95 per cent probability that an error lies between zero and twice the value of σ (exactly 1.96σ). At a 98 per cent probability the error $x = 2.5\sigma$.

It can be assumed frequently that σ is not dependent upon the location in the range to be applied in practice.

When the standard deviations have been obtained of two lines of position, whose intersection is the required position, the error of this position must be calculated.

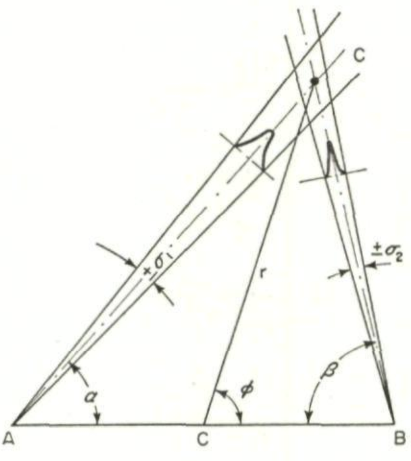

Fig. 1. Fixing error for direction finding

Figure 1 shows the position C, which is the intersection of the two beams originating in A and B, with its standard deviations, in this case the angles σ_1 and σ_2. The error pattern produced around C is of rhombic shape, if a rectangular error distribution of both standard deviations is assumed. But in fact it is a Gaussian error distribution (shown in Fig. 1) where the larger error is less probable than smaller ones. For this reason the error pattern is an ellipse and not a rhombus. The ellipse is a measure of the root mean square error.* This is valid for all types of lines of position. An enlarged view of the conditions existing around C is shown in Fig. 2 where it is

* It should be pointed out that aspect and axis ratio of the ellipse of uncertainty are influenced by correlation which as a rule occurs with hyperbolic systems. The influence is felt only when the correlation coefficients are large. A small amount of correlation changes only the value of $d_{\mathrm{r.m.s.}}$

assumed in addition that the beams originating in A and B appear as parallel lines in the distant point C because of the small values of σ. The root mean square error $d_{r.m.s.}$ is according to Trow and Jessell[1] and P. A. Mann[2]:

$$d_{r.m.s.} = c.\sigma \cdot \frac{2\pi}{360} \frac{\sqrt{\left\{2\left[\left(\frac{r}{c}\right)^2 + \frac{1}{4}\right]\left[\left(\left(\frac{r}{c}\right)^2 - \frac{1}{4}\right)^2 + \left(\frac{r}{c}\right)^2 \sin^2\phi\right]\right\}}}{(r/c)\sin\phi}$$

$$= c.\sigma.\delta$$

where r = distance to the base line centre
c = base line length
$\sigma_1 = \sigma_2$ assumed
ϕ = angle with the base line (cf. Fig. 1).

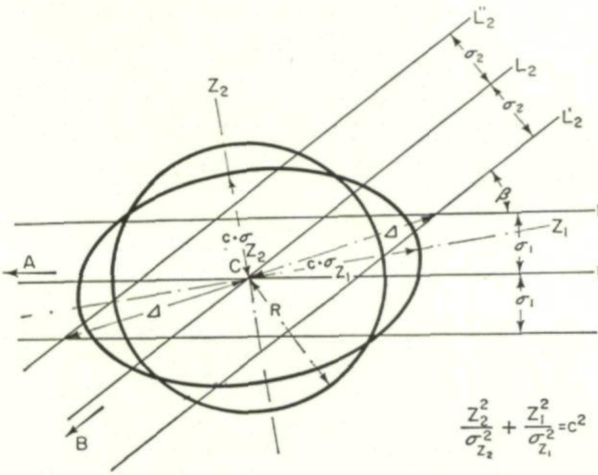

Fig. 2. Fixing error for intersection of two lines of position

It is possible to establish a value δ for each intersection C, i.e. for each r/c and ϕ, by means of which the position error $d_{r.m.s.}$ can be calculated, if the standard deviations σ are known. When all the values of equal $d_{r.m.s.}$ or δ are connected to each other, a pattern is obtained as shown in Fig. 3. It is evident that no useful bearings can be obtained along the line connecting both stations and that the maximum ranges of a given accuracy are located on the median perpendicular of the base line. It is also interesting to note that there is a region of maximum accuracy (minimum error) in the direction of the median perpendicular. This region is located at an angle of 35.5° as seen from the two stations.

3. THE RADIAL ERROR

The indication of the r.m.s. error is inaccurate. The Gaussian error function is valid only for the standard deviation of the individual lines of position. The magnitude of the positional error, i.e. the error in determining the intersection of two lines of position, follows a different error distribution

function which is steeper than the Gaussian error contour. Therefore the r.m.s. error does not give exactly the percentage of measurements which are located within a circle whose radius is equal to its value. It has been suggested, therefore, that the ship or the aircraft are given only the co-ordinate of its position and only a single error value, namely the radius of that circle within which the true position of the craft is located at a given probability (which will have to be indicated also) ; normally a 95 per cent probability is used.

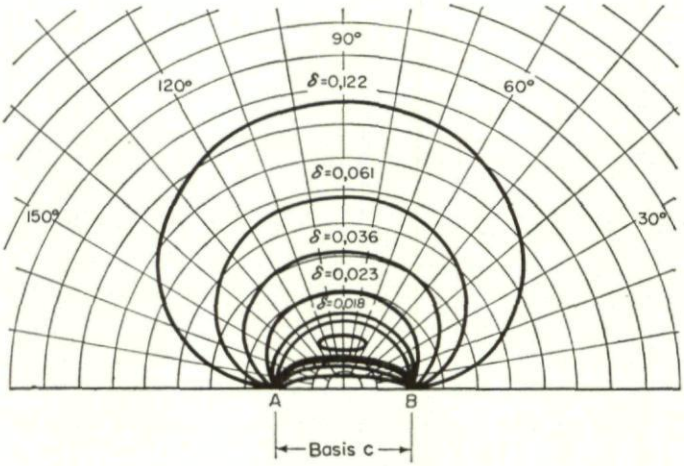

Fig. 3. Uniformed error δ as a function for azimuthal systems

The indication of this error of position means to the navigator that 19 out of 20 fixes are located within the circle of uncertainty.* The fixes are not distributed uniformly over the area of the circle, but this is of minor significance compared with the simplicity of presentation by a circle.

The task now is to calculate the radius of a circle enclosing 95 per cent of positional data, if the standard deviations of the two intersecting lines of position are known, i.e. the 95 per cent radial error.

3.1. *Azimuthal Systems* (*Systems with Intersecting Bearings*)

The calculation of the radial error (radius of the circle of uncertainty) of the azimuthal systems was accomplished by P. A. Mann[2,10]. The probability is:

$$W\left(\frac{R}{2c\sigma}\right) = \frac{2\sin^3\gamma}{\sin\alpha\sin\beta}\int_0^{(R/2c\sigma)^2} \exp\left[-z\,\frac{\sin^2\gamma(\sin^2\alpha+\sin^2\beta)}{\sin^2\alpha\sin^2\beta}\right] \times$$

$$\times\, J_0\left(\frac{iz\sin^2\gamma\,\sqrt{[(\sin^2\alpha+\sin^2\beta)^2 - 4\sin^2\alpha\sin^2\beta\sin^2\gamma]}}{\sin^2\alpha\sin^2\beta}\right)\mathrm{d}z$$

* Provided Gaussian distribution of position line errors.

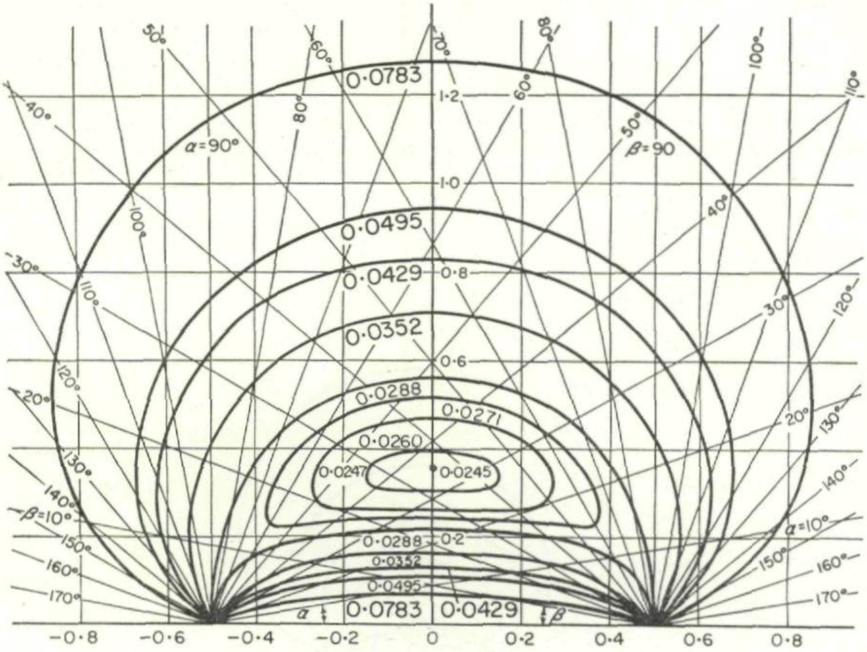

Fig. 4. Radial error R (90 per cent) for azimuthal systems

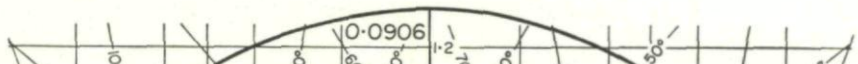

Fig. 5. Radial error R (95 per cent) for azimuthal systems

$$z = \frac{R^2}{4c^2\sigma^2}$$

R = radial error (radius of the circle of uncertainty)

c = length of the base line

α,β,γ = the three angles of the bearing triangle

J_0 = Bessel function of the first kind of zero order

The equation was interpreted and processed by the Institute of Mathematics of the Technical University of Darmstadt, i.e. the limits of the integral having the angles α, β, γ as parameters have been determined for a probability of 90 and 95 per cent. The results are shown on Figs. 4 and 5. The illustration is similar to that of the r.m.s. error in Fig. 3 ; however, the values deviate slightly.

A table is more convenient for practical purposes than a diagram. In Tables 1 and 2 those values are indicated with the bearing angles as parameters which, when multiplied by the base line length and the standard deviation, give the radial error.

3.2. *Rho–Theta System*

In the preceding subsection the azimuthal systems were described (restricted to the plane surface). These systems comprise the normal methods of ground direction finding, the airborne (shipborne) direction finding of omni-directional radio beacons and such systems as VOR (without DME), Navaglobe, etc. There are, however, two other groups of systems of radiolocation which have to be studied for the position error : the so-called Rho–Theta systems (where the position is determined from one bearing and one distance value) and the hyperbolic systems of navigation. At first, the Rho–Theta systems such as VOR + DME, TACAN and Navarho shall be discussed. For the radial error an integral is obtained (according to P. A. Mann) which is rather similar to that of the azimuthal systems :

$$W\left(\frac{R}{2\rho\sigma_\theta}\right) = \frac{2\rho\sigma_\theta}{\sigma_\rho}\int_0^{(R/2\rho\sigma_\theta)^2}\left\{\exp\left[-z\left(\frac{\rho^2\sigma_\theta^2}{\sigma_\rho^2}+1\right)\right]\times J_0\left[iz\left(\frac{\rho^2\sigma_\theta^2}{\sigma_\rho^2}-1\right)\right]\right\}\mathrm{d}z;$$

$$z = \frac{R^2}{4\rho^2\sigma_\theta^2}$$

Evaluation becomes difficult because the standard deviations σ_θ of the angle and σ_ρ of the distance occur together with the absolute distance ρ itself. The above equation can be simplified if it is assumed that the distance

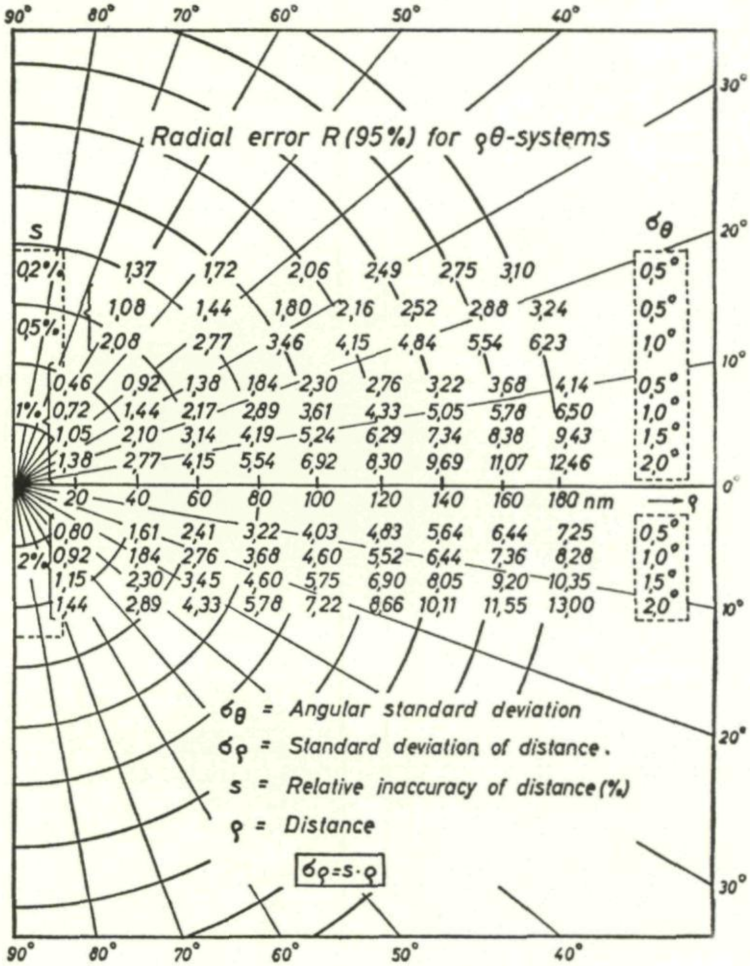

Fig. 6.

error is proportional to the distance itself, $\sigma_\rho = s.\rho$, with the initial error, if any, being considered later. Such a procedure is permitted with the systems and equipment used in practice. The equation so simplified can be solved properly. The result is shown in Fig. 6 and Table 3.

The curves of constant position errors are, of course, circles around the centre of the radio beacon station which provides the bearing and distance information. The radial errors, which are marked on the distance circles are dependent upon the accuracy of the bearing and of the distance. The area of uncertainty is also an ellipse whose size may be equal both in the

case of short distance and great standard deviation and if the distance is longer and the σ values are smaller. The figures presented indicate that the standard deviations of the distance are of influence only when the standard deviations of the angle are small and only in such cases when they are greater than 0.5 per cent of the distance.

3.3. *Hyperbolic Systems*

In the hyperbolic systems such as Decca, DECTRA, LORAN, etc., the calculation of the ellipse of uncertainty of any given probability, and its conversion into a circle of uncertainty, presents considerable mathematical problems. An extensive report[3] has been published by an American study team who studied the LF–LORAN system. Their findings were studied at a later date by the designers of the Decca system. The equation of the radial error has been evaluated graphically only. The following exact solution was accomplished by means of a digital computer. The equation reads:

$$W\left(\frac{R}{d_{\mathrm{r.m.s.}}}\ \varphi\right) = \frac{2}{\pi}\int_0^{\pi/2} \frac{1 - \exp\left[-\frac{1}{2}\left(\frac{R}{d_{\mathrm{r.m.s.}}}\right)^2\left(y+\frac{1}{y}\right)\left(\frac{1}{y}\cos^2\varphi + y\sin^2\varphi\right)\right] . \mathrm{d}}{\frac{1}{y}\cos^2\varphi + y\sin^2\varphi}$$

where φ = plane angle over which the integration has to be performed;

y = ratio of the standard deviations of the two intersecting hyperbolae, reduced, however, to rectangular coordinates, in other words, the ratio of the axes of the ellipse of uncertainty a/b,

$d_{\mathrm{r.m.s.}}$ = the root mean square error which is dependent upon the angle of intersection of the two hyperbolae

$$= \sqrt{\left(\frac{\sigma_1^2 + \sigma_2^2 + 2k_{12}\sigma_1\sigma_2\ \cos\beta}{\sin^2\beta}\right)}$$

where k_{12} = correlation coefficient of the two hyperbolic systems used for fixing, which may occur, for instance, when a common Master station is employed;

β = the angle of intersection of the hyperbolae in the position to be determined.

It is evident that the solution of the equation is extremely difficult. This solution is not universally applicable, but it is valid only for a definite configuration of the transmitting stations. For it is the configuration of the transmitting stations which determines the angles of intersection β of all points within the coverage.

Figure 7 illustrates the results of the calculation as obtained from a star configuration similar to that of the German chain of the Decca Navigator system (cf. also Section 3.3). If the transmitting stations are arranged differently, e.g. along an airway as in the case of DECTRA, the range contours are of a different shape.

4. CONCLUSIONS

It is assumed that the standard deviations σ of the line of position are known from practical experience made with all the radiolocation systems. Normally, the standard deviation is dependent upon the distance. Based

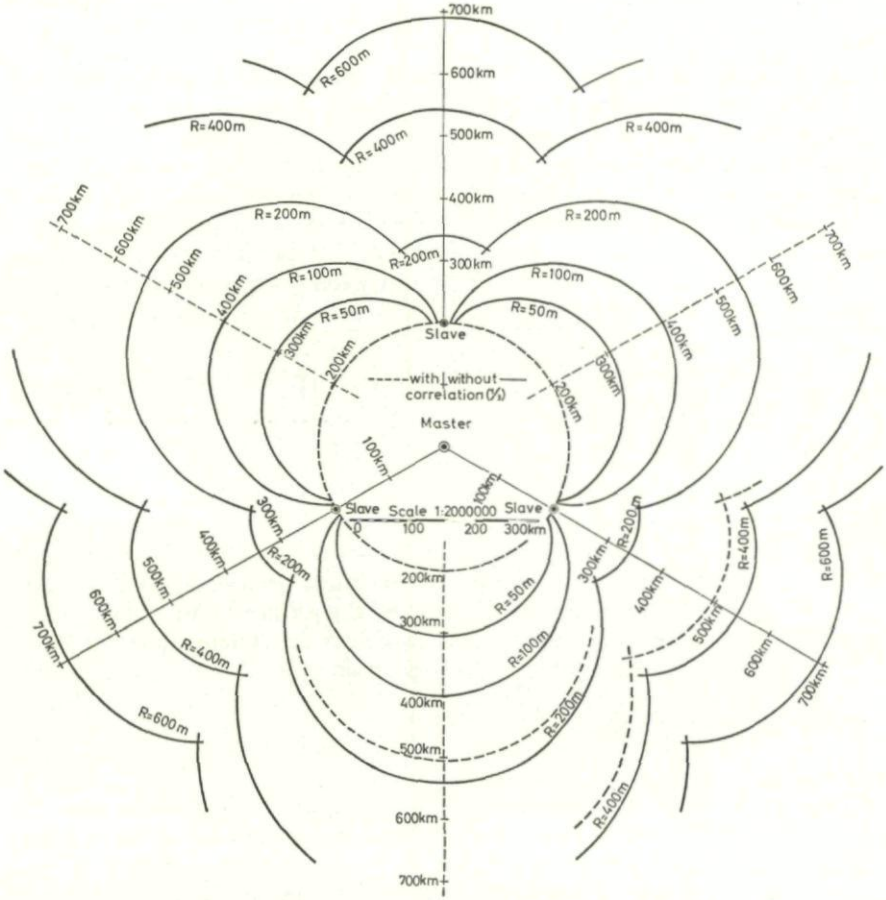

Fig. 7. Radial error R (95 per cent) in hyperbolic systems

Example: Symmetrical station lay-out for transmitters as Decca Distance Master–Slave 200 km.

Standard deviation = 10 m on the baseline, independent from distance.

on the above conditions and on a certain probability, the radii of the circles of uncertainty (radial errors) were calculated, dependent upon the position of the observer relative to the navigation system. The range or the coverage respectively obtainable at a given accuracy of position fixing were represented in a diagram. Thus the number of transmitting stations of each navigation system can be calculated which are required for covering

a certain area, if the position error shall not exceed a prescribed maximum value in all points within that area.

5. TABLES AND DIAGRAMS OF THE RADIAL ERROR OF RADIOLOCATION SYSTEMS

5.0. *Introduction*

The following tables and diagrams contain the radius R of the circle of uncertainty, i.e. the radial error, within which 95 per cent of all the values measured are located when a fix is established by means of a certain radiolocation system (95 per cent radial error). The values for a 90 per cent and 98 per cent probability are also given for some of the systems. The radial error is distinguished from the so-called r.m.s. error—which is frequently used in similar presentations because it can be calculated easily—in that it is an accurate measure of the error in terms of the probability calculation. The 95 per cent radial error R is equal to 1.96 times the r.m.s. error $d_{\text{r.m.s.}}$ if the angles of intersection are less than optimum. If there is an optimum angle of intersection, $R = 1.74\, d_{\text{r.m.s.}}$.

The radial error was calculated according to the integral equations given in the preceding section. The calculation was accomplished by the aid of digital computers.

The radial error is to be taken either directly from a table or from a diagram (Decca), or it is obtained by multiplying the value of the Table by the distance of the position from the centre of the system (Rho–Theta systems), or by the length of the base line (azimuthal systems).

The standard deviation σ peculiar to radiolocation systems may be dependent upon the time of the day or upon the season. This parameter has been taken into consideration in the tables, or it is introduced in the radial error as a constant of proportionality. *The tables cannot be used without knowledge of or certain assumptions on its magnitude.*

The contour of a constant radial error of the more important radiolocation systems is plotted on a map. In this manner contours or areas of coverage are obtained. Whenever possible, standardized values were used. It is possible to compare the coverage or the range of various systems by means of the charts, if certain assumptions are made on the standard deviation. The curvature of the earth was disregarded in all calculations or it has been proved that its influence at the given distances is very small (a few per cent) and that the radial error is reduced when it is taken into consideration.

5.1. *Azimuthal Systems*

(Establishing the bearing of two radio beacons by airborne (shipborne) equipment. Establishing the bearing of a craft by two ground direction finding stations.)

Tables 1 *and* 2

Figures 4 and 5 show a graph of the values of the table, namely contours of equal positional accuracy in the vicinity of two direction-finding stations. The graph should be turned downward around the x-axis to obtain the coverage of the " Azimuthal systems ".

5.2. *Rho–Theta System* (*Omni-directional Beacons*)

Table 3

A standard deviation σ_θ of the angle, and an accuracy of 's', expressed as a percentage of the distance ρ, were assumed. The standard deviation of the distance is $\sigma_\rho = s . \rho$.

The table contains the values by which the distance of the position from the centre of the radio beacon station must be multiplied to obtain the radial error R of the position, expressed in units of ρ (km or nautical miles).

$$R = \rho_{\underset{(\mathrm{km})}{\mathrm{n.m.}}} \times \text{value of the table}$$

The last column (over nautical miles) indicates the minimum distance whence the basic error of the radio beacon (which was assumed to be $\pm$ 0.2 n.m.) may be disregarded. If the distances are less than indicated in this column, or if the basic error is greater, allowance should be made accordingly by quadratic addition.

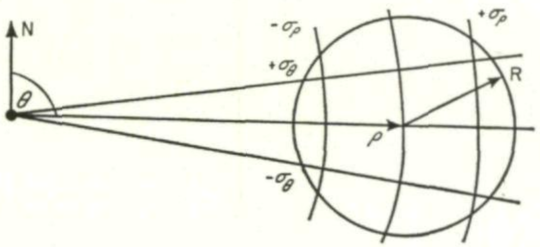

Figure 6 shows a graph of the values of the table, namely contours of equal positional accuracy around the v.h.f. omni-directional beacon. The values of σ_θ and s marked on the circles correspond to a 95 per cent probability. The coverage of the omni-directional beacon is of circular shape.

There is no error value s dependent upon the distance in the Navarho system. In this system the error is dependent upon the time. Under the condition that the error is 10^{-9} per hour* the phase error is 0.0013. fm (c/s) degrees.

Since the measuring frequency of fm c/s corresponds to a wavelength of $(3 \times 10^5/fm)$ km, the error of measurement is 1.1 km per hour.

The time-dependent error of measurement indicates the inaccuracy of the distance measurement. It can be taken into consideration by relating it to the distance measured. The error thus obtained (expressed in per cent) is looked up in the table (value of s) to find the radial error.

5.3. *Hyperbolic Systems*

No general table can be compiled for hyperbolic systems, because the position error depends upon the instantaneous angle of intersection of the hyperbolae. An example is given where a star configuration of the four

* In ref. 9 a frequency stability of 1×10^{-9} over 12 hours is given, which would be equivalent to an error of measurement of only approximately 100 m per hour.

transmitting stations was chosen, with one Master station located in the centre and three Slave stations located at the corners of an equilateral triangle, corresponding to the location of the transmitting stations of the *Decca Navigator System.*

The radial error as dependent on the distance was calculated with the

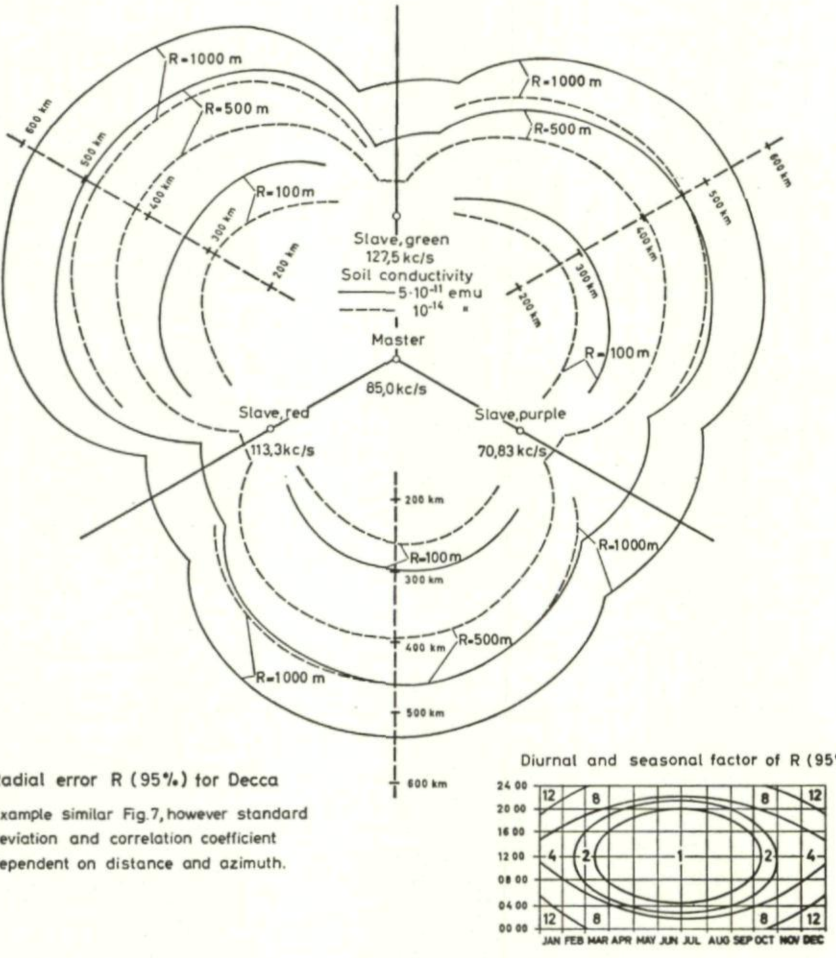

Fig. 8.

distance between Master and Slaves being 200 km. The results are shown in Fig. 7.

The solid curve refers to the 95 per cent radial error without correlation,*

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* Correlation in this context means the dependence or (undesired) coupling of the electromagnetic fields of both groups of transmitters whose hyperbolae are used for fixing purposes. such (undesired) coupling may be caused, for instance, by the Slave stations receiving distorted signals from the Master station and re-transmitting them, or the propagation paths in the ionosphere are influenced in a similar manner.

the dotted curve refers to a radial error with a correlation coefficient of $k = \frac{1}{3}$. In the Decca system, the correlation increases with the distance to the centre of the system from $k = 0$ to $k = \frac{2}{3}$ at the range limit. In LORAN–C (star configuration) k is $\frac{1}{3}$. Also in the case of LORAN a certain correlation ranging from 0 to 0.5 must be expected when a common transmitter is used for both hyperbolic patterns.

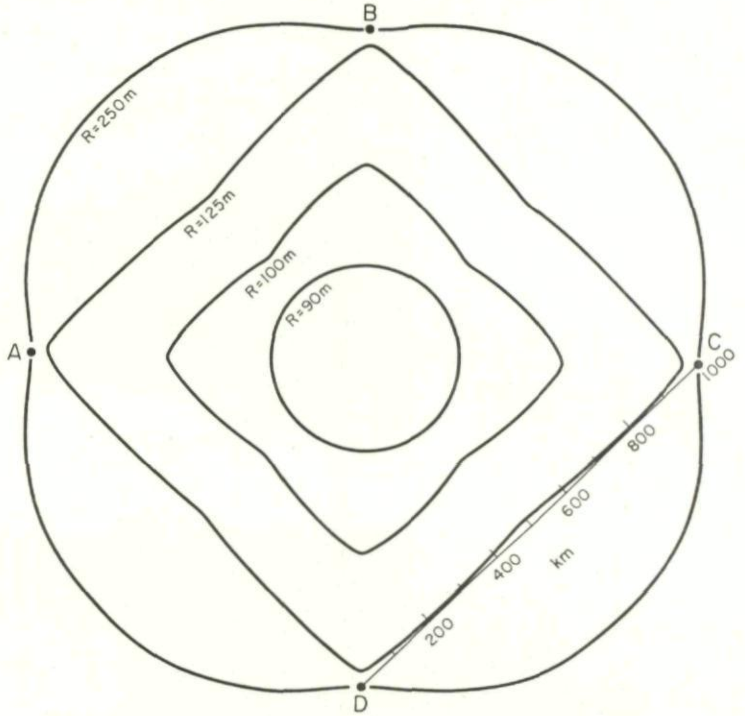

Fig. 9. LORAN-C, Radio-mailles (Radio-Web)
$\sigma_1 = \sigma_2 = 75m \triangleq 0.25\ \mu sec$
$AB = BC = CD = AD = 1000\ km$
Basis AC and BD
$= 1414\ km.$
Contours of 95 per cent radial error R.

In the calculation it was assumed that the standard deviation is a fraction of the distance of two adjacent hyperbolic patterns (10 m on the base line), which is independent of the distance. In reality, however, the standard deviation varies with the distance and with the time of the day or the season. This is due to the influence of the sky wave. It is possible also in this case to calculate the contours of the radial error. The calculation is, however, rather complicated for, dependent upon the instantaneous position of the observer, the field strengths of the sky wave and of the ground wave must be taken into consideration together with the ground conductivity and the frequency as parameters.[10,11] The ratio of sky wave amplitude to ground wave amplitude determines the magnitudes of σ and k.

Figure 8 shows the same case as illustrated in Fig. 7. The contours of the radial error are shown for propagation over an area of very good conductivity (sea water) and for propagation over soil of very poor conductivity.

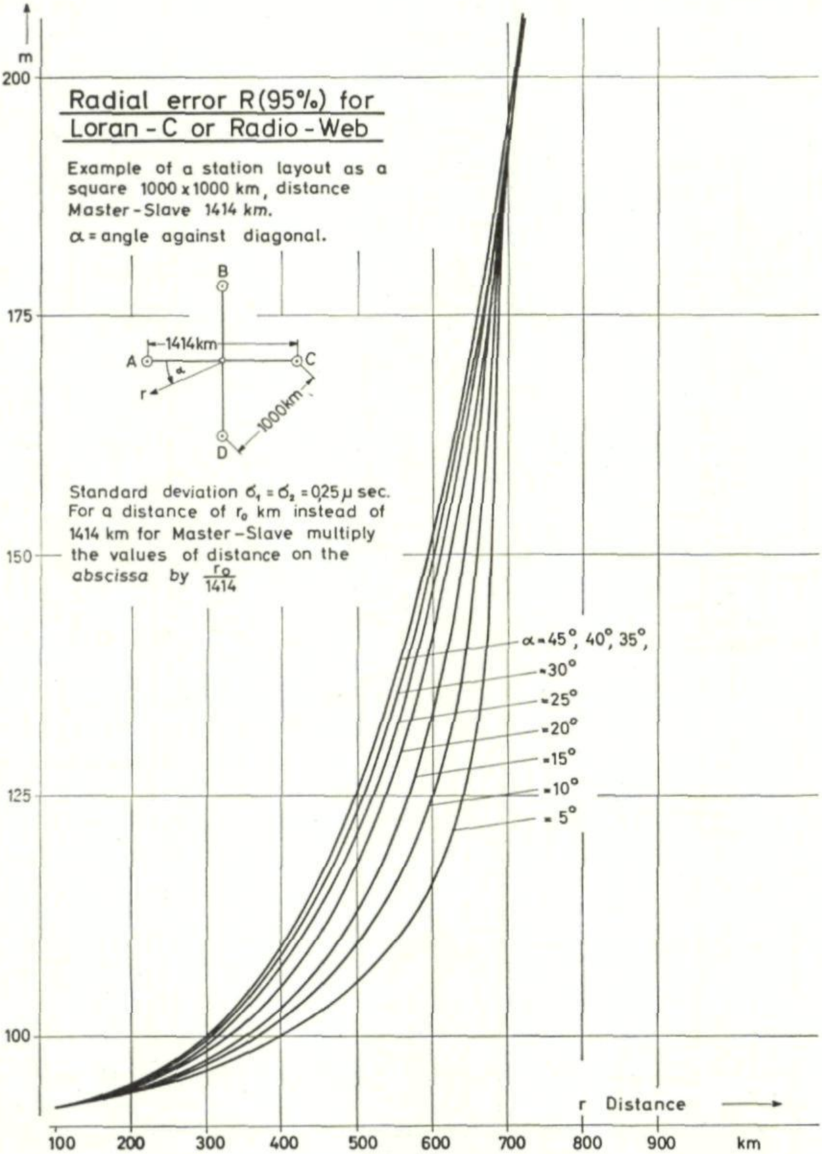

Fig. 10.

In the calculation the dependence upon the location of observation of the standard deviation and of the correlation coefficient is taken into account.*

* The calculations of the contours of R shown in Figs. 8, 9, 10 and 11 were accomplished by Ph. Hartl.

The influence of the time of the day and of the season should be taken into consideration by a factor indicated in the diagram on the bottom right of Fig. 8. Each value of R should be multiplied by this factor. A comparison of the values of Figs. 7 and 8 shows that the influence of the sky wave reduces by several times the accuracy of position fixing.

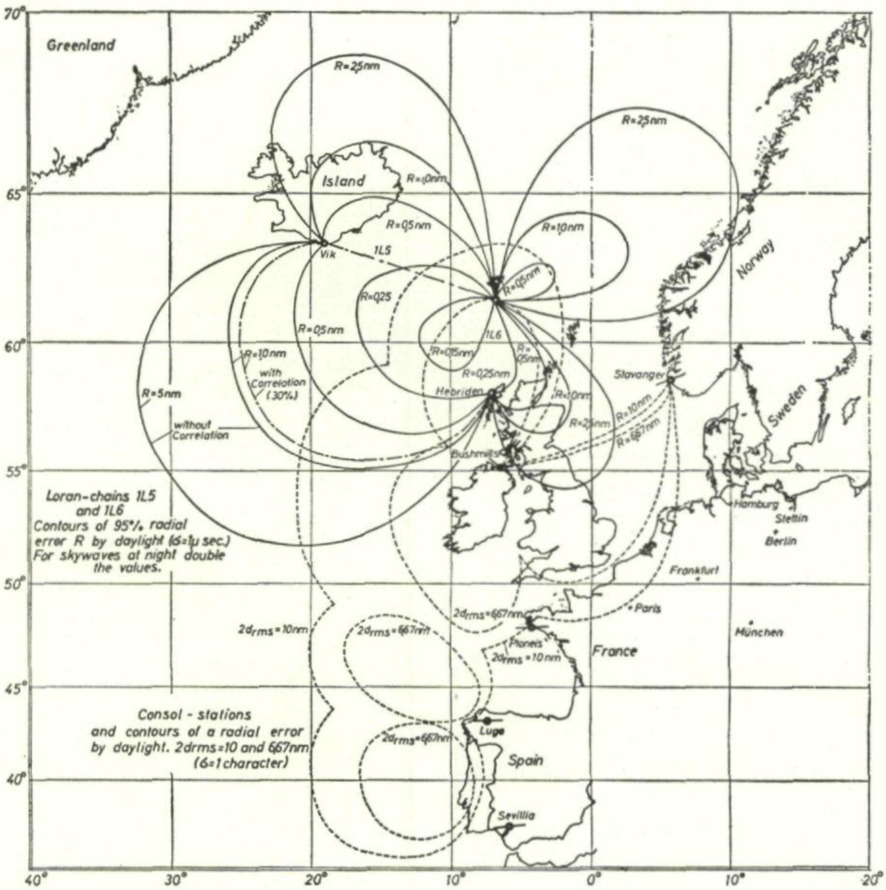

Fig. 11.

Figure 9 illustrates the contours of the 95 per cent radial error of the *LORAN-C* or the *Radio Mesh* systems. Also in this case the transmitting stations are assumed to be located at the corners of a square with the diagonal as base line.*

The values of R indicated refer to a distance of 1000 km between the transmitters. The standard deviation is 0.25 μsec. Figure 10 illustrates

* According to an American suggestion referring to LORAN-C, the side of the square is taken for the base line. The configuration with the diagonal as base line corresponds to the Radio Mesh system (conjugated equiphase lines).

the relationship between the radial error R and the distance to the centres of the square in the case of different angles. R can be taken from the diagram for any other point located within the area of coverage. In the case of different distances between Master and Slave stations, the diagram is changed to scale with the value of R remaining constant when it is assumed that the values of σ are independent of the length of the base line.*

According to the test data available, the influence of the sky wave may be disregarded over sea at ranges up to 2000 km.

If the configuration of the chain of transmitting stations used for locating purposes is not an equilateral triangle, as is the case, for instance, with the DECTRA system, and normally, with LORAN the shape of the area of coverage is changed accordingly. No standardized presentation can be given, because the radius of the circle of uncertainty is dependent upon the angle of intersection of the hyperbolae in the point of observation.

Figure 11 is a chart of the North Atlantic (mercator projection) on which the circles of uncertainty (with different radii) of the 1 *L* 5 and 1 *L* 6 *LORAN chains* are shown. It was assumed that the standard deviation of both chains is 1 μsec, a value derived from operational experience. When the sky wave is used, $\sigma = 2\ \mu$sec may be expected, with the values of the radial error being increased by a factor of 2. In order to be able to estimate the influence of the correlation, the contour of $R = 2$ km is shown and with without correlation ($\frac{1}{3}$).

It is of particular interest to note that no useful position information can be obtained on the extended line of connection between the transmitters, which is also the case in all " azimuthal systems " (cf. Figs. 5 and 7), for there the lines of position used for locating purposes are parallel.

The *CONSOL* system adopts a special position. This system was originally intended as an omni-directional radio range providing lines of position which are, strictly speaking, hyperbolae. The system may be used for position finding purposes, if the lines of position provided by two stations are measured. Trow and Jesell[1] describe a graphical method by means of which the contour of the r.m.s. error $d_{\text{r.m.s.}}$ can be drawn. Such contours have been published for $2d_{r.m.s.} = 10$ or 20 n.m. respectively under the condition that the standard deviation is one character at day and two or more characters at night,† depending on the distance.

It is possible to convert the $d_{\text{r.m.s.}}$ values into the radial error. However, conversion is a rather complicated procedure. No conversion has been accomplished because of the rather great variations of the σ values of CONSOL. However, the values of the r.m.s. error $d_{\text{r.m.s.}}$ were calculated numerically according to the equation of the hyperbolic methods and were drawn as a curve on the chart of the North Atlantic for double standard deviation in order to include a 95 per cent probability (Fig. 11). These contours coincide with the contours constructed graphically. They also

* This assumption is an arbitrary one. The law governing the degree of dependency on the distance cannot be inferred from the test data available.

† H. Keeling reports that the location at night over sea was based on two characters at distances of 100–200 and over 600 n.m.; three-and-a-half characters at distances of 200–300 and 500–600 n.m.; six characters at distances of 400–500 n.m.; six-and-a-half characters at distances of 300–400 n.m.

show the coverage with a position error of 10 and 6.67 n.m. (18.5 and 12.4 km) at day time. The standard deviation was one character.

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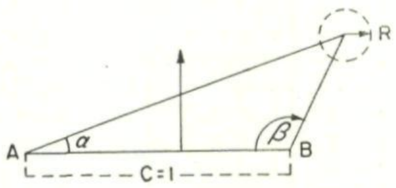
Table 1.

Accuracy of a Radio Bearing

The Table contains the radial error R (radius of the circle of uncertainty) related to the base line $c = 1$ and the standard deviation $\delta = 1^0$, dependent on the angles α and β between the radio beams and the base line.

The probability W at which the point of measurement is located within the circle of uncertainty is 90 *per cent.*

$$\underset{\text{n.m.}}{R} = \underset{\text{n.m.}}{c} \; . \; \underset{\text{degree}}{\sigma} \times \text{value of table}$$



α *in Degrees*	$\beta = 5°$	$\beta = 10°$	$\beta = 15°$	$\beta = 20°$	$\beta = 25°$
005	0.1171	0.0830	0.0668	0.0566	0.0494
010	0.0830	0.0597	0.0494	0.0434	0.0393
015	0.0668	0.0494	0.0411	0.0364	0.0334
020	0.0566	0.0434	0.0364	0.0324	0.0299
025	0.0494	0.0393	0.0334	0.0299	0.0277
030	0.0442	0.0363	0.0314	0.0283	0.0264
035	0.0402	0.0339	0.0299	0.0272	0.0256
040	0.0371	0.0322	0.0288	0.0266	0.0253
045	0.0348	0.0308	0.0280	0.0262	0.0252
050	0.0329	0.0297	0.0275	0.0261	0.0253
055	0.0315	0.0289	0.0272	0.0262	0.0257
060	0.0303	0.0284	0.0271	0.0264	0.0263
065	0.0295	0.0281	0.0272	0.0269	0.0272
070	0.0290	0.0280	0.0275	0.0276	0.0283

Table 1. *Continued*

α in Degrees	β = 5°	β = 10°	β = 15°	β = 20°	β = 25°
075	0.0286	0.0281	0.0281	0.0286	0.0297
080	0.0285	0.0284	0.0288	0.0298	0.0315
085	0.0286	0.0290	0.0298	0.0314	0.0337
090	0.0290	0.0298	0.0312	0.0333	0.0365
095	0.0295	0.0308	0.0328	0.0358	0.0400
100	0.0304	0.0322	0.0350	0.0389	0.0444
105	0.0315	0.0340	0.0376	0.0428	0.0501
110	0.0329	0.0363	0.0411	0.0479	0.0577
115	0.0348	0.0392	0.0455	0.0545	0.0680
120	0.0372	0.0429	0.0452	0.0636	0.0826
125	0.0402	0.0477	0.0590	0.0763	0.1043
130	0.0442	0.0542	0.0698	0.0952	0.1391
135	0.0494	0.0632	0.0857	0.1251	0.2006
140	0.0565	0.0761	0.1106	0.1775	0.3282
145	0.0665	0.0959	0.1536	0.2850	
150	0.0815	0.1294	0.2404		
155	0.1058	0.1953			
160	0.1511				

W 90%

α in Degrees	β = 30°	β = 35°	β = 40°	β = 45°	β = 50°
005	0.0442	0.0402	0.0371	0.0348	0.0329
010	0.0363	0.0339	0.0322	0.0308	0.0297
015	0.0314	0.0299	0.0288	0.0280	0.0275
020	0.0283	0.0272	0.0266	0.0262	0.0261
025	0.0264	0.0256	0.0253	0.0252	0.0253
030	0.0253	0.0248	0.0246	0.0248	0.0252
035	0.0248	0.0245	0.0245	0.0249	0.0256
040	0.0246	0.0245	0.0249	0.0255	0.0265
045	0.0248	0.0249	0.0255	0.0265	0.0279
050	0.0252	0.0256	0.0265	0.0279	0.0296
055	0.0259	0.0266	0.0279	0.0296	0.0319
060	0.0268	0.0279	0.0296	0.0319	0.0349
065	0.0281	0.0296	0.0318	0.0348	0.0386
070	0.0297	0.0317	0.0346	0.0384	0.0435
075	0.0316	0.0343	0.0381	0.0431	0.0498
080	0.0341	0.0376	0.0425	0.0491	0.0580
085	0.0371	0.0418	0.0482	0.0570	0.0691
090	0.0409	0.0471	0.0556	0.0675	0.0845
095	0.0458	0.0540	0.0655	0.0821	0.1066
100	0.0522	0.0632	0.0792	0.1030	0.1403
105	0.0606	0.0758	0.0987	0.1347	0.1952
110	0.0721	0.0938	0.1282	0.1863	0.2947
115	0.0884	0.1209	0.1761	0.2795	0.5059
120	0.1129	0.1648	0.2623	0.4766	
125	0.1524	0.2433	0.4439		
130	0.2226	0.4081			
135	0.3694				

Table 1. *Continued*

α in *Degrees*	$\beta = 55°$	$\beta = 60°$	$\beta = 65°$	$\beta = 70°$	$\beta = 75°$
005	0.0315	0.0303	0.0295	0.0290	0.0286
010	0.0289	0.0284	0.0281	0.0280	0.0281
015	0.0272	0.0271	0.0272	0.0275	0.0281
020	0.0262	0.0264	0.0269	0.0276	0.0286
025	0.0257	0.0263	0.0272	0.0283	0.0297
030	0.0259	0.0268	0.0281	0.0297	0.0316
035	0.0266	0.0279	0.0296	0.0317	0.0343
040	0.0279	0.0296	0.0318	0.0346	0.0381
045	0.0296	0.0319	0.0348	0.0384	0.0431
050	0.0319	0.0349	0.0386	0.0435	0.0498
055	0.0349	0.0388	0.0437	0.0502	0.0588
060	0.0388	0.0438	0.0505	0.0593	0.0712
065	0.0437	0.0505	0.0594	0.0716	0.0886
070	0.0502	0.0593	0.0716	0.0889	0.1141
075	0.0588	0.0712	0.0886	0.1141	0.1534
080	0.0703	0.0878	0.1134	0.1528	0.2183
085	0.0864	0.1119	0.1512	0.2167	0.3371
090	0.1096	0.1486	0.2136	0.3334	0.5926
095	0.1449	0.2089	0.3272	0.5837	
100	0.2028	0.3187	0.5704		
105	0.3078	0.5530			
110	0.5314				

W 90%

α in *Degrees*	$\beta = 80°$	$\beta = 85°$	$\beta = 90°$	$\beta = 95°$	$\beta = 100°$
005	0.0285	0.0286	0.0290	0.0295	0.0304
010	0.0284	0.0290	0.0298	0.0308	0.0322
015	0.0288	0.0298	0.0312	0.0328	0.0350
020	0.0298	0.0314	0.0333	0.0358	0.0389
025	0.0315	0.0337	0.0365	0.0400	0.0444
030	0.0341	0.0371	0.0409	0.0458	0.0522
035	0.0376	0.0418	0.0471	0.0540	0.0632
040	0.0425	0.0482	0.0556	0.0655	0.0792
045	0.0491	0.0570	0.0675	0.0821	0.1030
050	0.0580	0.0691	0.0845	0.1066	0.1403
055	0.0703	0.0864	0.1096	0.1449	0.2028
060	0.0878	0.1119	0.1486	0.2089	0.3187
065	0.1134	0.1512	0.2136	0.3272	0.5704
070	0.1528	0.2167	0.3334	0.5837	
075	0.2183	0.3371	0.5926		
080	0.3384	0.5970			
085	0.5970				

Table 1. *Continued*

α in Degrees	$\beta = 105°$	$\beta = 110°$	$\beta = 115°$	$\beta = 120°$	$\beta = 125°$
005	0.0315	0.0329	0.0348	0.0372	0.0402
010	0.0340	0.0363	0.0392	0.0429	0.0477
015	0.0376	0.0411	0.0455	0.0512	0.0590
020	0.0428	0.0479	0.0545	0.0636	0.0763
025	0.0501	0.0577	0.0680	0.0826	0.1043
030	0.0606	0.0721	0.0884	0.1[illegible]29	0.1524
035	0.0758	0.0938	0.1209	0.1648	0.2433
040	0.0987	0.1282	0.1761	0.2623	0.4439
045	0.1347	0.1863	0.2795	0.4766	
050	0.1952	0.2947	0.5059		
055	0.3078	0.5314			
060	0.5530				

α in Degrees	$\beta = 130°$	$\beta = 135°$	$\beta = 140°$	$\beta = 145°$	$\beta = 150°$
005	0.0442	0.0494	0.0565	0.0665	0.0815
010	0.0542	0.0632	0.0761	0.0959	0.1294
015	0.0698	0.0857	0.1106	0.1536	0.2404
020	0.0952	0.1251	0.1775	0.2850	
025	0.1391	0.2006	0.3282		
030	0.2226	0.3694			
035	0.4081				

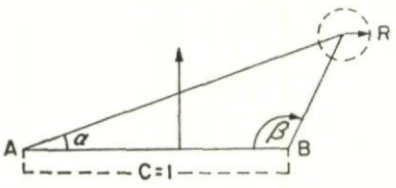
α in Degrees	$\beta = 155°$	$\beta = 160°$
005	0.1058	0.1511
010	0.1953	

Table 2. Accuracy of a Radio Bearing

The Table contains the radial error R (radius of the circle of uncertainty) related to the base line $c = 1$ and the standard deviation $\sigma = 1^0$, dependent on the angles α and β between the radio beams and the base line.

The probability W at which the point of measurement is located within the circle of uncertainty is *95 per cent.*

$R = c \times \sigma \times$ value of the table
n.m. n.m. degree



α in Degrees	$\beta = 5°$	$\beta = 10°$	$\beta = 15°$	$\beta = 20°$	$\beta = 25°$
005	0.1394	0.0988	0.0795	0.0673	0.0588
010	0.0988	0.0710	0.0588	0.0517	0.0468
015	0.0795	0.0588	0.0489	0.0433	0.0397
020	0.0673	0.0517	0.0433	0.0383	0.0353
025	0.0588	0.0468	0.0397	0.0353	0.0326
030	0.0526	0.0432	0.0372	0.0334	0.0309
035	0.0479	0.0404	0.0355	0.0322	0.0300
040	0.0442	0.0383	0.0342	0.0314	0.0295
045	0.0414	0.0366	0.0333	0.0310	0.0294
050	0.0392	0.0354	0.0327	0.0308	0.0297
055	0.0374	0.0344	0.0323	0.0309	0.0302
060	0.0361	0.0338	0.0322	0.0313	0.0309
065	0.0352	0.0334	0.0324	0.0319	0.0320
070	0.0345	0.0333	0.0328	0.0328	0.0334
075	0.0341	0.0335	0.0334	0.0339	0.0351
080	0.0340	0.0338	0.0343	0.0354	0.0373
085	0.0341	0.0345	0.0355	0.0373	0.0399
090	0.0345	0.0354	0.0371	0.0396	0.0432
095	0.0352	0.0367	0.0391	0.0425	0.0474
100	0.0361	0.0384	0.0416	0.0462	0.0527
105	0.0375	0.0405	0.0448	0.0509	0.0595
110	0.0392	0.0432	0.0489	0.0569	0.0686
115	0.0414	0.0466	0.0541	0.0649	0.0809
120	0.0442	0.0511	0.0610	0.0757	0.0983
125	0.0479	0.0568	0.0702	0.0909	0.1242
130	0.0526	0.0646	0.0831	0.1133	0.1656

Table 2. Continued

α in Degrees	$\beta = 5°$	$\beta = 10°$	$\beta = 15°$	$\beta = 20°$	$\beta = 25°$
135	0.0588	0.0752	0.1020	0.1489	0.2389
140	0.0673	0.0906	0.1317	0.2113	0.3907
145	0.0792	0.1142	0.1829	0.3393	
150	0.0970	0.1541	0.2862		
155	0.1259	0.2325			
160	0.1799				

W 95%

α in Degrees	$\beta = 30°$	$\beta = 35°$	$\beta = 40°$	$\beta = 45°$	$\beta = 50°$
005	0.0526	0.0479	0.0442	0.0414	0.0392
010	0.0432	0.0404	0.0383	0.0366	0.0354
015	0.0372	0.0355	0.0342	0.0333	0.0327
020	0.0334	0.0322	0.0314	0.0310	0.0308
025	0.0309	0.0300	0.0295	0.0294	0.0297
030	0.0295	0.0287	0.0285	0.0287	0.0292
035	0.0287	0.0282	0.0282	0.0286	0.0295
040	0.0285	0.0282	0.0284	0.0292	0.0303
045	0.0287	0.0286	0.0292	0.0302	0.0318
050	0.0292	0.0295	0.0303	0.0318	0.0339
055	0.0301	0.0307	0.0320	0.0339	0.0367
060	0.0313	0.0323	0.0341	0.0367	0.0402
065	0.0328	0.0344	0.0368	0.0402	0.0449
070	0.0347	0.0370	0.0402	0.0447	0.0508
075	0.0371	0.0402	0.0445	0.0504	0.0584
080	0.0401	0.0442	0.0499	0.0577	0.0684
085	0.0438	0.0492	0.0568	0.0672	0.0818
090	0.0484	0.0556	0.0657	0.0799	0.1002
095	0.0543	0.0640	0.0777	0.0974	0.1267
100	0.0619	0.0750	0.0940	0.1224	0.1669
105	0.0719	0.0901	0.1174	0.1603	0.2324
110	0.0857	0.1116	0.1526	0.2218	0.3509
115	0.1052	0.1439	0.2097	0.3327	0.6022
120	0.1344	0.1962	0.3123	0.5674	
125	0.1814	0.2896	0.5285		
130	0.2651	0.4858			
135	0.4397				

Table 2. Continued

α in Degree	$\beta = 55°$	$\beta = 60°$	$\beta = 65°$	$\beta = 70°$	$\beta = 75°$
005	0.0374	0.0361	0.0352	0.0345	0.0341
010	0.0344	0.0338	0.0334	0.0333	0.0335
015	0.0323	0.0322	0.0324	0.0328	0.0334
020	0.0309	0.0313	0.0319	0.0328	0.0339
025	0.0302	0.0309	0.0320	0.0334	0.0351
030	0.0301	0.0313	0.0328	0.0347	0.0371
035	0.0307	0.0323	0.0344	0.0370	0.0402
040	0.0320	0.0341	0.0368	0.0402	0.0445
045	0.0339	0.0367	0.0402	0.0447	0.0504
050	0.0367	0.0402	0.0449	0.0508	0.0584
055	0.0403	0.0449	0.0510	0.0589	0.0692
060	0.0449	0.0511	0.0591	0.0697	0.0841
065	0.0510	0.0591	0.0699	0.0846	0.1050
070	0.0589	0.0697	0.0846	0.1054	0.1356
075	0.0692	0.0841	0.1050	0.1356	0.1824
080	0.0832	0.1041	0.1347	0.1818	0.2598
085	0.1024	0.1329	0.1799	0.2579	0.4014
090	0.1302	0.1768	0.2542	0.3970	0.7055
095	0.1724	0.2487	0.3896	0.6949	
100	0.2414	0.3794	0.6791		
105	0.3665	0.6583			
110	0.6326				

W 95%

α in Degree	$\beta = 80°$	$\beta = 85°$	$\beta = 90°$	$\beta = 95°$	$\beta = 100°$
005	0.0340	0.0341	0.0345	0.0352	0.0361
010	0.0338	0.0345	0.0354	0.0367	0.0384
015	0.0343	0.0355	0.0371	0.0391	0.0416
020	0.0354	0.0373	0.0396	0.0425	0.0462
025	0.0373	0.0399	0.0432	0.0474	0.0527
030	0.0401	0.0438	0.0484	0.0543	0.0619
035	0.0442	0.0492	0.0556	0.0640	0.0750
040	0.0499	0.0568	0.0657	0.0777	0.0940
045	0.0577	0.0672	0.0799	0.0974	0.1224
050	0.0684	0.0818	0.1002	0.1267	0.1669
055	0.0832	0.1024	0.1302	0.1724	0.2414
060	0.1041	0.1329	0.1768	0.2487	0.3794
065	0.1347	0.1799	0.2542	0.3896	0.6791
070	0.1818	0.2579	0.3970	0.6949	
075	0.2598	0.4014	0.7055		
080	0.4029	0.7108			
085	0.7108				

Table 2. Continued

α *in Degrees*	$\beta = 105°$	$\beta = 110°$	$\beta = 115°$	$\beta = 120°$	$\beta = 125°$
005	0.0375	0.0392	0.0414	0.0442	0.0479
010	0.0405	0.0432	0.0466	0.0511	0.0568
015	0.0448	0.0489	0.0541	0.0610	0.0702
020	0.0509	0.0569	0.0649	0.0757	0.0909
025	0.0595	0.0686	0.0809	0.0983	0.1242
030	0.0719	0.0857	0.1052	0.1344	0.1814
035	0.0901	0.1116	0.1439	0.1962	0.2896
040	0.1174	0.1526	0.2097	0.3123	0.5285
045	0.1603	0.2218	0.3327	0.5674	
050	0.2324	0.3509	0.6022		
055	0.3665	0.6326			
060	0.6583				

α *in Degrees*	$\beta = 130°$	$\beta = 135°$	$\beta = 140°$	$\beta = 145°$	$\beta = 150°$
005	0.0526	0.0588	0.0673	0.0792	0.0970
010	0.0646	0.0752	0.0906	0.1142	0.1541
015	0.0831	0.1020	0.1317	0.1829	0.2862
020	0.1133	0.1489	0.2113	0.3393	
025	0.1656	0.2389	0.3907		
030	0.2651	0.4397			
035	0.4858				

α *in Degrees*	$\beta = 155°$	$\beta = 160°$
005	0.1259	0.1799
010	0.2325	

Table 3. The Radial Error R (Radius of the Circle of Uncertainty) of Rho–Theta Navigation Systems

	Probability Degrees	90 per cent	95 per cent	98 per cent	— over n.m.
$s = 0.2$ per cent $\sigma_\theta =$	0.5	0.0342	0.0403	0.0475	20
	1.0	0.0403	0.0460	0.0527	20
	1.5	0.0501	0.0575	0.0622	20
	2.0	0.0620	0.0722	0.0843	20
	2.5	0.0750	0.0882	0.1037	20
	3.0	0.0887	0.1047	0.1236	10
	3.5	0.1026	0.1215	0.1436	10
	4.0	0.1167	0.1385	0.1637	10
	5.0	0.1450	0.1722	0.2040	10
	6.0	0.1734	0.2062	0.2444	10
$s = 1.0$ per cent $\sigma_\theta =$	0.5	0.0201	0.0230	0.0264	20
	1.0	0.0310	0.0361	0.0421	20
	1.5	0.0443	0.0524	0.0618	20
	2.0	0.0583	0.0692	0.0818	20
	2.5	0.0725	0.0861	0.0020	20
	3.0	0.0867	0.1031	0.1222	10
	3.5	0.1010	0.1201	0.1424	10
	4.0	0.1153	0.1372	0.1627	10
	5.0	0.1439	0.1713	0.2032	10
	6.0	0.1725	0.2055	0.2438	10
$s = 0.5$ per cent $\sigma_\theta =$	0.5	0.0155	0.0180	0.0211	40
	1.0	0.0292	0.0346	0.0409	40
	1.5	0.0434	0.0516	0.0611	20
	2.0	0.0576	0.0686	0.0813	20
	2.5	0.0720	0.0857	0.1016	20
	3.0	0.0863	0.1027	0.1219	10
	3.5	0.1006	0.1198	0.1422	10
	4.0	0.1149	0.1369	0.1625	10
	5.0	0.1426	0.1711	0.2030	10
	6.0	0.1723	0.2053	0.2436	10
$s = 0.2$ per cent $\sigma_\theta =$	0.5	0.0145	0.0172	0.0204	40
	1.0	0.0288	0.0342	0.0406	40
	1.5	0.0431	0.0513	0.0609	20
	2.0	0.0574	0.0684	0.0812	20
	2.5	0.0718	0.0855	0.1015	20
	3.0	0.0861	0.1026	0.1218	10
	3.5	0.1005	0.1197	0.1421	10
	4.0	0.1149	0.1368	0.1624	10
	5.0	0.1436	0.1710	0.2030	10
	6.0	0.1723	0.2052	0.2436	10

σ_θ = standard deviation of the angle
σ_ρ = standard deviation of the distance.
ρ = distance.
s = inaccuracy of distance expressed in per cent.
$R = \rho \times$ value of the table.

4. INTRODUCTION TO THE TABLES

T. von Hauteville

4.1. General Information on Radio Navigation Systems.

4.2. Navigational Considerations on the Radio Navigation Systems.

4.3. Comparison of the Expenditure for the Radio Navigation Systems.

The tables contain the general physical and technical data (Table 4.1), considerations on the navigational use including operation of the equipment (Table 4.2) and data on the expenditure involved (Table 4.3). The tables allow a comparison and facilitate the evaluation of the various characteristics of the different systems.

In each table the same vertical column refers to the same system.

Blank boxes indicate that no information was available. A stroke in a box indicates that the question is not proved right for the system.

Table 4.1. *General information on radio navigation systems* presents the essential physical and technical data that are given with more detail in the relevant system description.

Table 4.2. *Navigational considerations on the radio navigation systems* is divided into the following sub-sections:

4.2.1. Airborne (shipborne) use;

4.2.2. Air traffic control considerations;

4.2.3. Operation of the equipment.

Sub-section 4.2.1 is based on the type of radio coordinates (radial, circular or hyperbolic lines of position) provided by a system in the form of a visual or aural display.

Except for the case of homing where the bearing is referred to a fixed line on the craft all other systems provide radio coordinates with reference to the geographical position of the ground station or references lines fixed in space. In principle, radio coordinates can only serve a navigational purpose if they can be referred to geographical coordinates which is normally done by plotting them on a map. Depending on the system and the purpose, different kinds of plotting are used.

The methods customary for air navigation, specially in the case of medium-distance traffic, are normally others than those suitable for maritime navigation. The continuous indication of the geographical position of the aircraft is secondary to the pilot, provided that sufficient height above ground makes obstacles negligible.

To know the maintenance of the intended track above ground is of primary importance. It is therefore desirable for air navigation systems to obtain as direct as possible appropriate instrument indications from the radio coordinates.

The direction, fixed in space, to or from a ground station should be either directly indicated on board as a radio-coordinate or the left/right deviation of the course-line—selected on the omni-bearing selector—should be indicated on a cross-pointer instrument. The cross-pointer instrument is also the standard instrument for course direction of the Instrument Landing system. That shows clearly the practical compatibility of navigation systems providing bearing information with the ICAO instrument landing system. The direct maintenance of the intended course according to instrument indication, without computer, or map, and a simple connection of the automatic pilot is of course only possible if the navigation system and the geographical situation permit the coincidence of the radio coordinates with air or seaways.

All airways navigation requirements are met, if a navigation system supplies additionally to the bearing information also continuous and unambiguous distance indication and thus the position of the craft without requiring further evaluation.

Even for the case that the radio coordinates do not coincide with the intended course the same navigational application is possible, if intermediate computers are available which give the desired information (heading, deviation, distance, etc.). The amount of expenditure for intermediate computers depends largely on the systems with regard to the different radio-coordinate patterns (Polar-coordinates, Hyperbola-pattern).

Flight logs or visual position displays supply no information suitable for direct course flying if no additional computers or similar facilities are used. They provide for *indirect flying* where the course resp. the necessary corrections have to be derived by a mental process from the recorded track.

Sub-section 4.2.2 deals with questions relating to the close relationship of position finding, navigation and air traffic control.

The answers to the majority of questions contained in sub-section 4.2.3 are not dependent upon the system but refer to the mechanical and electrical design, for instance manual or remote tuning of the equipment. It is possible, for instance, to provide a system which supplies position information with a pictorial display (map) of the position.

Table 4.3. *Comparison of the expenditure for the radio navigation systems.* When the values of the tables are compared, it should be borne in mind that the information is based on very different sources. It is not always evident from the figures available which services are included or are not included respectively. This is particularly true for values referring to systems which are still under development or of which only a few pilot installations exist.

Table 4.1. General Information on Radio Navigation Systems

	Direction Finding (2.01)	*CONSOL* (2.02)	*Navaglobe* (2.03)	*VOR* (2.04)	*TACAN* (2.05)	*VORTAC VOR/DMET* (2.06)	*Navarho* (2.07)	*Decca* (2.08)
4.1.01 Type of magnitude measured or observed	Angle	Number of signals until equisignal is observed	Amplitude ratios	Phase differences	Phase difference and time of travel		Amplitude ratios and phase difference	Phase differences
4.1.02 Type of radio coordinates	Bearings				Bearings and distances			Distance differences
4.1.03 Type of the line of position	Radial lines of position				Radial and circular lines of position			Hyperbolic lines of position
4.1.04 Primary application in air or marine navigation: short-range or coastal navigation <50 n.m. S medium range or homing (approaching land) 30 . . . 300 n.m. M long-range or transocean navigation >200 n.m. L	S, M	M, L	M, L	S, M not applicable in marine navigation	S, M	S, M	M, L	S, M
4.1.05 Number of fixed transmitting stations required to determine: a line of position a position	1 2	1 2	1 2	1 2	1 1	1 1	1 1	2 3
4.1.06 Number of carrier frequencies required to determine: a line of position a position	airborne shipborne 1 1 2 1[a]	1 2	1 2	2 2	1 2	1 3	1 1[a]	2 3, 4[b]
4.1.07 Frequency band according to ITU Regulations (Genf 1959) in which the system operates or is expected to operate	200–415 kc/s	Some installations 192 and 194 kc/s	90–110 kc/s	112–118 Mc/s	965–1215 Mc/s	112–118 and 965–1215 Mc/s	90–110 kc/s	70–130 kc/s
4.1.08 Type of modulation	airborne shipborne A_1, A_0/A_2 A_2	A_0/A_1	A_1	A_2/F2	P2D/P2F	A_2/F2 (VOR) P2F (DMET, VORTAC)	A_1	A_0
4.1.09 Bandwidth of transmission according to ITU Regulations (Genf 1959)	*ca.* 50 c/s 2000 c/s	*ca.* 50 c/s	*ca.* 50 c/s	*ca.* 20 kc/s	*ca.* 1 Mc/s	*ca.* 20 c/s (VOR) *ca.* 1 Mc/s (DMET, VORTAC)	250 c/s[a]	50 c/s 20 c/s[b]
4.1.10 Power transmitted per station, expressed in kW	0.1–0.3 Some installations to 5	1.5–5	4	0.05 or 0.2	7.5 peak power	0.2 (VOR) + 7.5 peak power (VORTAC)	Experimental installation 4 planned 100	2 × 2.4[a] or 3 × 2.4[b] or 4 × 1,2
4.1.11 Antenna base line expressed in wavelength (λ) or nautical miles (n.m.)	0	6λ	$\frac{1}{3}\lambda$	0	0	0	$\frac{1}{3}\lambda$	*ca.* 80–130 n.m.
4.1.12 Scattering parameter σ	0.5° (equipment)	Daytime, one signal; nightime 2–6 signals		± 1.2°	Azimuth ± 0.4–1.1°; inaccuracy of distance ± 0.1 n.m.	Azimuth 1.2° inaccuracy of distance ± 0.1 n.m.		σ depends very much on distance, this applies also to the correlation coefficient (see 2.08.3 and 3.3)
4.1.13 Status of availability (1961)	Available since 1912	Available since 1942	One experimental installation 1954	Available since 1948	Available since 1954	Available since 1959	One experimental installation 1956	Available since 1944

	DECTRA (2.09)	*STANDARD-LORAN* (2.10)	*LORAN-C* (2.11)	*Radio–Mesh* (*Radio–Mailles Radio–Web*) (2.12)	*DELRAC and Omega* (2.13)	*Navarho–H* (2.14)	*Navarho–HH* (2.15)	*Navarho–Rho* (2.16)
4.1.01 Type of magnitude measured or observed		Time differences	Time differences and phase differences	Time interval separating the passage of equiphase lines	Phase differences	Amplitude ratios and phase difference	Phase differences	
4.1.02 Type of radio coordinates				Conjugated equiphase lines	Distance differences	Bearings and distance differences	Distance differences	Distances
4.1.03 Type of the line of position				Small area of position-hyperbolic lines	Hyperbolic lines of position	Radial and hyperbolic lines of position	Hyperbolic lines of position	Circular lines of position
4.1.04 Primary application in air or marine navigation	L	M, L	S, M, L	S, M, L	M, L	M, L	M, L	M, L not applicable in marine navigation
4.1.05 Number of fixed transmitting stations required to determine: a line of position a position	2 4	2 3	2 4[c], 3[d]	2 4[c], 3[d]	2 3	1 2	2 3	1 2
4.1.06 Number of carrier frequencies required to determine: a line of position a position	1 2	1 1[a]	1 1[a]	3[a] 4	1 (2 or 3 with coarse position finding) 1 (2 or 3 with coarse position finding)	1 2	2 3	1 2
4.1.07 Frequency band according to ITU Regulations (Genf 1959) in which the system operates or is expected to operate	70–130 kc/s	1800–2000 kc/s	90–110 kc/s	Experimental network 1800–2000 kc/s planned: 90–110 kc/s; for M + L	10–14 kc/s	90–110 kc/s	90–110 kc/s	90–110 kc/s
4.1.08 Type of modulation	A_0	P_0	P_0	A_2 experimental network	A_0	A_1	A_0	A_1
4.1.09 Bandwidth of transmission according to ITU Regulations (Genf 1959)	*ca.* 60 c/s[a]	*ca.* 50 kc/s	*ca.* 20 kc/s	Experimental network *ca.* 800 c/s planned *ca.* 350 c/s[e]	5 c/s	*ca.* 50 c/s		*ca.* 250 c/s[a]
4.1.10 Power transmitted per station, expressed in kW	4	100 peak power some installations 1000	60–200 planned 1000 } Peak power	Experimental installation 0.1, planned 100	DELRAC: planned 5 Omega: planned 100	100	100	100
4.1.11 Antenna base line expressed in wavelength (λ) or nautical miles (n.m.)	*ca.* 80 and *ca.* 2000 n.m.	200–400 n.m.	*ca.* 600–1000 n.m.	Experimental installation 60 n m. planned 600 n m.	DELRAC: 750–1000 n.m. Omega: . . . 5000 n.m.	$\frac{1}{3}\lambda$ and *ca.* 1000 n.m.	*ca.* 1000 n.m.	*ca.* 1000 n m.
4.1.12 Scattering parameter σ		Ground wave 1–4 μsec sky wave 6–8 μsec	0.1–0.2 μsec					
4.1.13 Status of availability (1961)	In operation since 1957	Available since 1942	Several chains in operation since 1959	One experimental installation S since 1956: planned M, L	Preliminary experiments since 1956	Planned	Planned	Planned

(*a*) See system description. (*b*) Mark 10 only. (*c*) For areas of position. (*d*) For intersecting hyperbolae. (*e*) Pulse modulation requires greater bandwith. (*f*) Ninety-five per cent of all the bearings between the double deviation ($\pm 2\sigma$).

REMARKS ON TABLES 4.2.1 AND 4.2.2

1 — Information refers to the radio compass.
2 — Information refers to the rotating-loop, goniometer or cathode-ray tube direction-finders.
3 — Is, however, determined by the number of signals.
4 — Affirmative with dual airborne equipment at the intersection of two radial lines of position.
5 — Over VOR.
6 — If provided with additional equipment TACAN (data link).
7 — Affirmative in the case of the Decca Flight Log Mark 10 within one lane.
8 — Affirmative with additional equipment (under development).
9 — Affirmative when the radio coordinate coincides with intended track.
10 — Expressed as numbers of the grid square, the rectangular coordinates *X*, *Y* or hyperbolic coordinates.

4.3 *Comparison of the Investment required for Ground-Installation of Radio Navigation Systems*

		Direction Finding (2.01) *Air*	*Sea*		*CONSOL* (2.02)	*Navaglobe* (2.03)	*VOR* (2.04)	*TACAN* (2.05)	*VORTAC VOR/DMET* (2.06)	*Navarho* (2.07)	*Decca* (2.08)	*DECTRA* (2.09)	*STANDARD-LORAN* (2.10)	*LORAN-C* (2.11)	*Radio-Mesh (Radio-Mailles Radio-Web)* (2.12)	*DELRAC and Omega* (2.13)	*Navarho-H* (2.14)	*Navarho-HH* (2.15)	*Navarho-Rho* (2.16)
4.3.1	*Ground installation* Number of fixed transmitting stations required to determine a line of position a position (drift)	1 2	1 2		1 2	1[5] 2[5]	1 2	1 1	1 1	1[5] 1[5]	2[12] 3[12]	2[20] 3[20]	2 3	2 3 (4)[25]	— 4	2 3	1 2	2 3	— 2
4.3.1.1 4.3.1.1.1	Price of the equipment in thousand DM RF and modulation equipment with power pack, excluding aerial		land 12	light ship 12		1200		250[7]		1400[10],[11]	282[13]								
4.3.1.1.2	Standby equipment for 1.1 with automatic change-over facility	21.5	12[4]	12[4]	250	1200		not applicable, see 4.3.1		1400	in 4.3.1.1								
4.3.1.1.3	Monitoring unit within the equipment		2	2			132[6]	50	450[8],[28] 300[9],[28]	400	in 4.3.1.1	1250[21]	800[24]	1600[26]		4000 or 12000[27]			
4.3.1.1.4	Monitoring unit—field of radiation		not provided		10			22			30[14]								
4.3.1.1.5	Aerial with feeder and material for the counterpoise	5	2.1	1.0	250	640	16, included in 4.3.1.1	in 4.3.1.1		640	40–100 according to area and operation 40[15]								
4.3.1.1.6	Set of operating tubes	0.5	0.35	0.35	1.0		3.6	28			5	12							
4.3.1.2	Buildings																		
4.3.1.2.1	Transmitter huts, offices, including separate huts for monitoring and aerial tuning equipment, cubage (m^3)	40–70	40	15	300	2500[28]	150	100	150	2500[28]	1300	1300 (0)[16]	900	1000[28]					
4.3.1.2.2 4.3.1.2.2.1	*Aerials* Number of aerials	1	1	1	3	3	1	1	2	3	1 (+ 1)[15]	1	1	1					
4.3.1.2.2.2	Aerial height above ground (m)	30	30	20	100	200	9	6	11	200	100 (30)[15]	168	90	300					
4.3.1.2.2.3	Type of aerial	Self-radiating tower or T-aerial	T-aerial	T-aerial	Self-radiating towers	Self-radiating towers	Cage aerial + dipole	Directional aerial with rotating reflectors	Cage aerial and directional aerial with rotating reflectors[8] cage aerial + collinear dipoles[9]	Self-radiating towers	Prism aerial or T-aerial	Prism aerial	Self-radiating tower or T-aerial	Umbrella aerial					
4.3.1.2.3	Counterpoise per metre of conduit	360 (12 × 30)	360–750	not applicable	3 × 1000	247500 (900 × 275)	not applicable	not applicable	not applicable	247500 (900 × 275)	10000 (100 × 100)	18300 (100 × 183)	12000	54000 (300 × 180)					
4.3.1.2.4	Connected power kVA	1.5	1	1	15		5.5	30	30[8],[28] 10[9],[28]	360	15	50 (40)[16]	15						
4.3.1.3	Construction and placing into service of each transmitting station—hours Equipment including power pack, aerial, feeder, however, without power supply equipment	50–60	50–60	50–60	1000[28]	6000	500	1000[28]	1500[28]	6000	1700[18]	1800[22]							
4.3.1.4 4.3.1.4.1	Commissioning Commissioning tests of the complete installation per transmitter station	10	10	10			90	120[28]	150[28]		100	100							
4.3.1.4.2 4.3.1.4.2.1	Flight calibration checks or calibrations checks on board of ships, including evaluation Hours of flight or travel resp.	5	50	50			15	15[28]	15[28]		[19]	[23]							
4.3.1.4.2.2	Working hours	10	50	50			100	120[28]	120[28]		[19]	[23]							
4.3.1.5	Current cost of operation per transmitting station																		
4.3.1.5.1	Cost of valves per year, in thousand DM	0.25[1]	0.24	0.24			5.4				6.2	18 (12)[16]	15						
4.3.1.5.2	MWh required per year	15	3	3			30			TDM 60	120 (100)[16]	350 (240)[16]							
4.3.1.5.3	Personel required for 24 hours of operation (skilled and unskilled personel)	0.06 (0.25)[2]	0.25	0.25	5		0.5			12	5 (3)[16]	5 (3)[16]	2 engineers 3 technicians						
4.3.1.5.4	Maintenance cost per year for items 4.3.1.1 to 4.3.1.5 in thousand DM	0.5[2]	0.3	0 3			2.8[3]			24	10[3]	10[3]							
4.3.1.5.5	Rent for monitoring lines, in thousand DM		not required				*ca.* 4.2			not applicable	not applicable	not applicable							
4 3.1.5.6	Flight, sea and ground surveys, hours needed per year	4	4	4			40				300[17]								

REMARKS ON TABLE 4.2.3

1 — Information refers to the radio compass.
2 — Information refers to medium-frequency direction-finders including cathode-ray tube direction-finders according to the Watson–Watt principle.
3 — Affirmative for equipment with tuning indicator permitting the identification to be checked.
4 — No ambiguities present.
5 — By sensing.
6 — No aural indication of the positional data when cathode-ray tube direction-finders (according to Watson–Watt) are used.
7 — Only when the goniometer type direction-finder TELEGON III is used—with special indicator tube.
8 — Shorter when cathode-ray tube direction-finders are used.
9 — Incorporated test circuit for the electrical symmetry of the antenna installation and input circuit with TELEGON direction-finders. With cathode-ray tube direction-finders (according to Watson–Watt) only the receiver symmetry can be checked.
10 — Each time with cathode-ray tube direction-finders (according to Watson–Watt).
11 — When automatic direction-finders are used in aviation: remote control.
12 — " Possible " means: appropriate design of the equipment is recommended.
13 — Only coarse ambiguity without navigational significance.
14 — Only manual control of small airborne systems such as NARCO and " Private Flyer TACAN ".
15 — For DME portion.
16 — Decca Navigator with Decometer indication, affirmative in the case of Mark 10 Decca Navigator with Flight Log.
17 — With distorted geographical coordinate system.
18 — Maximum 60 sec of transmission of the coarse pattern must be waited for.
19 — By decometer indication also possible at any time during flight, when Mark 8 is used only when the zone is identified.
20 — Only at chart change (Flight Log).
21 — Incorporated test circuit of the phase of the receiver and interpretation circuit.
22 — Ambiguity of position only close to the extended base line.
23 — Operational control of noise level and interpretation circuit.
24 — With Marconi Lodestar.
25 — When a distance computer is used.
26 — In microseconds—travelling time.
27 — Flag alarm: automatic checking of the receiver output.

	Direction Finding (2.01) *Airborne*[1]	*Direction Finding* (2.01) *Shipborne*[2]	*CONSOL* (2.02)	*Navaglobe* (2.03)	*VOR* (2.04)	*TACAN* (2.05)	*VORTAC VOR/DMET* (2.06)	*Navarho* (2.07)	*Decca* (2.08)	*DECTRA* (2.09)	*STANDARD-LORAN* (2.10)	*LORAN-C* (2.11)	*Radio-Mesh (Radio-Mailles Radio-Web)* (2.12)	*DELRAC and Omega* (2.13)	*Navarho-H* (2.14)	*Navarho-HH* (2.15)	*Navarho-Rho* (2.16)
4.2.3 *Operation* 4.2.3.1 Method of operation 4.2.3.1.1 Is manual operation performed immediately on the equipment?	yes[11]	yes	yes[11]	no	no[14]	no[14]	no[14]	no	yes[16]	no	yes	yes	yes	no	no	no	no
4.2.3.1.2 Is operation accomplished by remote control?	yes	no	no	yes	yes	yes	yes	yes	yes[16]	yes	no	no	possible[12]	yes	yes	yes	yes
4.2.3.2 Operational functions 4.2.3.2.1 Frequency adjustment 4.2.3.2.1.1 Is the operation channelized?	yes	no	no	yes	yes[14]	yes[14]	yes[14]	yes	yes	yes	yes	yes	possible[12]	yes	yes	yes	yes
4.2.3.2.1.2 Is continuous tuning provided?	yes	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no
4.2.3.2.1.2.1 Aural indication?	yes	yes	yes	—	—	—	—	—	—	—	—		—	—	—	—	—
4.2.3.2.1.2.2 Visual indication?	yes[3]	yes[3]	yes[3]	—	—	—	—	—	—	—	—		—	—	—	—	—
4.2.3.2.2 Is adjustment required because the indication is dependent upon the field strength?	no	yes no[24]	yes	no	no	no	no	no	no	no	yes	no	no	no	no	no	no
4.2.3.2.3 Must navigational ambiguities be resolved?	no[4]	yes	yes	yes[13]	no	no	no	yes[13]	yes	yes	yes[22]	no	no	yes[13]	yes	yes	yes
4.2.3.2.3.1 Is resolution achieved by adjustment of the equipment?	—	yes[5]	no	no	—	—	—	no	no[16]	no	no	—	—	no	no		no
4.2.3.2.3.2 Is resolution achieved by dead reckoning?	—	yes	yes	yes	—	—	—	yes	yes	yes	yes	—	—	yes	yes	yes	yes
4.2.3.2.4 Other manipulations required 4.2.3.2.4.1 Is it necessary to introduce into the system the initial position to obtain correct positional data?	no	no	no	no	no	no	no	yes[15]	yes[19]	yes	no	no			no	no	yes
4.2.3.2.4.2 Is another single or multiple or repeated calibration of the equipment necessary to obtain useful positional data?	no	no[10]	no	no	no	no	no	no	yes[20]	no	no	no			no	no	no
4.2.3.3 Obtaining the positional data 4.2.3.3.1 Are the positional data indicated 4.2.3.3.1.1 Aurally?	no	yes[6]	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no
4.2.3.3.1.2 Visually (*a*) by pointer instrument?	yes	yes[7],[24]	possible[12]	yes	yes	yes	yes	yes	yes[16]	yes	no	no	no	yes	yes		
(*b*) by counter?	no	no	possible[12]	no	no	yes[15]	yes[15]	yes[15]	no	no	no	yes	yes	no	yes[15],[25]	yes[26]	yes[15]
(*c*) by cathode-ray tube?	no	yes[6]	no	no	no	no	no	no	no	no	yes	no	no	no	no	no	no
(*d*) by pictorial display?	no	no	no	no	no	possible[12]	possible[12]	possible[12]	no	no	no		possible[12]	no	possible[12]	no	no
(*e*) by flight log course recorder?	no	no	no	no	no	no	no	no	yes[17]	yes[17]	no		no	yes[17]	no	no	no
4.2.3.3.2 Time required 4.2.3.3.2.1 Time elapsed (in seconds) between correct frequency adjustment and first unambiguous fixing result (line of position (l.o.p.) and position (pos.))?	immediately (l.o.p.)	approx. 30[8] (l.o.p.) 5[24] (l.o.p.)	approx. 60 (l.o.p.)	immediately (l.o.p.)	immediately (l.o.p.)	max. 20	bearing immediately (l.o.p.) range max. 20	immediately (pos.)	immediately[18]	immediately[18]	approx. 30 . . . 60 (l.o.p.)		immediately	approx. 30			
4.2.3.3.2 Is the indication continuous and automatic?	yes (l.o.p.)	no yes[24]	no	yes (l.o.p.)	yes (l.o.p.)	yes (pos.)	yes (pos.)	yes (pos.)	yes (pos.)	yes (pos.)	yes (l.o.p.)	yes (pos.)	yes (pos.)		yes (pos.)	yes (pos.)	yes (pos)
4.2.3.3.2.3 Is failure of the equipment indicated? 4.2.3.3.2.3.1 By arbitrary checking process?	no	yes[9]	not required	no	no	no	no	no	yes[21]	yes[21]	yes[23]						
4.2.3.3.2.3.2 By automatic indication?	no	no	not required	yes[27]	yes[27]	yes[27]	yes[27]	yes[27]	yes	yes	not required				yes[72]	yes[27]	yes[27]

REMARKS ON TABLE 4.3.1

1 — Dual installation.
2 — Includes time of travel.
3 — Two per cent of the value of the equipment; the actual cost is lower.
4 — Without automatic change-over function.
5 — The complete installation consists of three transmitters of 15 kW each, with reserve and three aerials.
6 — Price of the dual installation 200 W, DM 96,000.
7 — For model GRN 9A.
8 — For VOR dual installation of 200W and single TACAN installation of 7 kW.
9 — VOR and DMET dual installation of 200W and 1 kW resp.
10 — All data taken from ICAO, Doc. 7831.
11 — Price of three 15 kW transmitters (each DM 40,000), including atomic clock (DM 180,000). For one transmitter of 100 kW the price is DM 1.200,000.
12 — Decca chains usually consist of one Master station and three Slave stations.
13 — The price stated is the FOB UK price of one station of the Decca chain (average) without Mark 10 operation. For Mark 10 operation the average price of one station is increased to DM 353,000.
14 — Increase up to 70.62 thousand DM for one Mark 10 Decca chain (cf. 13).
15 — Standby aerial with construction of the foundation of the aerial tower.
16 — Slave stations in brackets.
17 — Refers to the German chain only.
18 — Installation of the control facilities with automatic change-over function approximately 100 hr, installation of the transmitter and of the cable to the aerial without excavation work approximately 300 hr, assembly of the mast approximately 100 hr, excavation work (counterpoise and cable installation) approximately 300 hr.
19 — No flight commissioning tests are usually performed with the Decca system since the errors occurring may be neglected. As regards the determination of systematic errors of airports and runways, the determination with evaluation without flying hours takes approximately 5 hr. (Observations are made on the ground only.) For a precise determination of port entrances or a landfall approximately 14 days on board of a ship are needed for each chain, or approximately 700 hr of observation in a vehicle on land. The time required for evaluation may be neglected.
20 — Normally the DECTRA installation is implemented by supplementation of two Decca stations. The additional equipment required when Decca installations are used is indicated in brackets; if there is no value given in brackets, no supplementation is possible and the

expenditure indicated is required independently of the existence of a Decca chain. The values given in the first place thus indicate the expenditure required for the DECTRA installation if it is set up independently of the Decca system.

21 — Expenditure in addition to the Decca installation approximately 60 per cent.

22 — With DECTRA approximately as 18, but increased by 100 hr if a Decca–DECTRA ground station is concerned. The construction of a DECTRA ground station requires the same amount of hours as a Decca station.

23 — Flight tests are not normally performed, one installation is undergoing tests, otherwise as 19.

24 — All information obtained from Report on Electronic Systems of Air Navigation PB 111344.

25 — For medium-distance navigation, installation on the corners of a quadrilateral is suggested.

26 — According to ICAO Doc. 7831, the price of a LORAN-C installation is approximately twice the price of a Standard-LORAN installation.

27 — DM 4 million for a pair of DELRAC stations; DM 12 million of Omega, according to ICAO Doc. 7831.

28 — Estimated.

4.2. *Navigational Consideration*

		Direction Finding (2.01) *Airborne*[1]	*Shipborne*[2]	*CONSOL* (2.02)	*Navaglobe* (2.03)	*VOR* (2.04)	*TACAN* (2.05)	*VORTAC VOR/DMET* (2.06)	*Navarho* (2.07)	*Decca* (2.08)	*DECTRA* (2.09)	*STANDARD-LORAN* (2.10)	*LORAN-C* (2.11)	*Radio-Mesh (Radio-Mailles/ Radio-Web)* (2.12)	*DELRAC and Omega* (2.13)	*Navarho-H* (2.14)	*Navarho-HH* (2.15)	*Navarho-Rho* (2.16)
4.2.1	*Airborne aspects of the systems*																	
4.2.1.1	General navigational properties and applications with chart interpretation (marine and air navigation).																	
4.2.1.1.1	Type of radio coordinate																	
4.2.1.1.1.1	Does the system supply radial lines of position (bearings)?	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no	no		no	yes	no	no
4.2.1.1.1.1*a*	Are such bearings determined from airborne or shipborne reference lines?	yes	yes	no	no	no	no	no	no	—	—	—	—	—	—	no	—	—
4.2.1.1.1.1*b*	Are such bearings transmitted and indicated as related to geographical lines of reference (e.g. magnetic true north)?	no	no	yes	yes	yes	yes	yes	yes	—	—	—	—	—	—	yes	—	—
4.2.1.1.1.2	Does the system supply circular lines of position (distance)?	no	no	no	no	no	yes	yes	yes	no	no	no	no	no	no	no	no	yes
4.2.1.1.1.2*a*	Is the distance indicated as primary coordinate (transponder principle)?	—	—	—	—	—	yes	yes	no	—	—	—	—	—	—	no	—	no
4.2.1.1.1.2*b*	Is the distance indicated as difference relative to an initial value?	—	—	—	—	—	no	no	yes	—	—	—	—	—	—	no	—	yes
4.2.1.1.1.3	Does the system provide hyperbolic lines of position (distance difference)?	no	no	no	no	no	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes	no
4.2.1.1.1.3*a*	Are the distance differences indicated as primary coordinates?	—	—	—	—	—	—	—	—	yes	yes	yes	yes	no	yes	yes	yes	no
4.2.1.1.1.3*b*	Are the data indicated as determined from several such distance difference values obtained by processing?	—	—	—	—	—	—	—	—	yes	no	no	—	yes	no	no	yes	no
4.2.1.1.1.4	Is the radio coordinate indicated continuously (cont.) or as single value (SV)?	cont.	SV	SV	cont.	cont.	cont.	cont.	cont.	cont.	cont	SV	cont.	cont.	cont.	cont.	cont.	cont.
4.2.1.1.2	Chart interpretation of the radio coordinate																	
4.2.1.1.2.1	Can the radio coordinate be plotted on a chart immediately (without intermediate computation)?	yes	yes	no	yes	yes	yes	yes	yes	no	no	no	no	no	no	no	no	yes
4.2.1.1.2.2	Is the line of position obtained by using a special chart with grid overlay, or from tables?	no	no	yes	no	no	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes	no
4.2.1.1.2.3	Is an automatic and continuous display of the radio coordinates on a chart possible by using presently available equipment (pictorial display—flight log)?	no	no	no	no	no	yes	yes	yes	yes	yes	no		yes	—		yes	—
4.2.1.1.2.3*a*	Is the chart utilized correct in angular representation (*ta*) or distorted (*d*)?	—	—	—	—	—	ta	ta	ta	d	d	—		ta	d	ta	d	—
4.2.1.1.2.3*b*	Is the initial position set automatically?	—	—	—	—	—	yes	yes	yes	no[7]	no[7]	—		yes	—		no	—
4.2.1.1.3	How is the position obtained?	intersections of radial lines of position					intersections of radial and circular lines of position			intersections of hyperbolic lines of position				grid square[10]	intersections of hyperbolic lines of position	intersections of radial and hyperbolic lines of position	intersections of hyperbolic lines of position	intersections of circular lines of position
4.2.1.2	Navigational application without charts by using the indicator readings of the radio coordinate only (primarily in aviation).																	
4.2.1.2.1	Immediate track guidance through the use of a radio coordinate, indication of the deviation from a straight line of position.																	
4.2.1.2.1.1	Can the radio coordinate be set as intended track?	no	no	no[3]	yes	yes	yes	yes	yes	no	no[9]	no	no	no	no	yes	no	no
4.2.1.2.1.2	Is the magnitude of the deviation from the intended track displayed by a Left/Right indicator?	no	no	no	yes	yes	yes	yes	yes	no[8]	no	no	no	no	no	yes	no	no
4.2.1.2.2	Is the distance of the aircraft to the ground station indicated?	no	no	no	no	no	yes	yes	yes	no	no	no	no	no	no	yes	no	yes
4.2.2	*Additional consideration of the systems with respect to air traffic control.*																	
4.2.2.1	Simultaneous use of the navaid channel for communications																	
4.2.2.1.1	Ground-to-air																	
4.2.2.1.1.1	Are the messages received by all users?	—	—	—	—	yes	no	yes[5]	—	—	—	—	—	—	—	—	—	—
4.2.2.1.1.2	Are the messages received by selected stations?	—	—	—	—	no	yes[6]	yes[6]	—	—	—	—	—	—	—	—	—	—
4.2.2.1.1.2*a*	Number of users?	—	—	—	—	—	100	100	—	—	—	—	—	—	—	—	—	—
4.2.2.1.1.2*b*	At what time intervals?	—	—	—	—	—	$2\frac{2}{3}$ s	$2\frac{2}{3}$ s	—	—	—	—	—	—	—	—	—	—
4.2.2.1.2.	Air-to-ground																	
4.2.2.1.2.1	Number of users able to communicate on a single channel?	—	—	—	—	—	100	100	—	—	—	—	—	—	—	—	—	—
4.2.2.1.2.2	At what time intervals?	—	—	—	—	—	$2\frac{2}{3}$ s	$2\frac{2}{3}$ s	—	—	—	—	—	—	—	—	—	—
4.2.2.2	Execution of holding manoeuvres																	
4.2.2.2.1	At the location of the ground station?	yes	—	—	—	yes	yes	yes	—	yes	—	—	—	no	—	—	—	—
4.2.2.2.2	Offset from the ground station?	no	—	—	—	no[4]	yes	yes	—	yes	—	—	—	yes	—	—	—	—

REMARKS ON TABLE 4.3.2

1 — Bendix DFA 70.

2 — Collins DF 201.

3 — Marconi CMA 301.

4 — Battery-supplied rotating-loop direction-finder for medium frequencies for ships not required by law to carry radio equipment.

5 - Goniometer direction-finder, for medium frequencies for ships required by law to carry radio equipment.

6 — Goniometer direction-finder with display portion, for medium frequencies, for ships required by law to carry radio equipment.

7 — Cathode-ray tube direction-finder according to the Watson–Watt principle.

8 — Single installation according to " Navarho Navigation " published by the Federal Telecommunication Laboratories, June 1957.

9 — Collings 51 R3 with omni-bearing selector and course deviations indicator, may also be used as v.h.f. communication receiver and for ILS.

10 — Bendix MN 85, with omni-bearing selector and course deviation indicator, may also be used as v.h.f. communication receiver and for ILS.

11 — Small-scale equipment for private aircraft NARCO Omnigator Mark 2, Model VTR 2: v.h.f. communication and navigation receiver with omni-bearing selector and course deviation indicator and v.h.f. communication transmitter and 75 Mc/s position marker receiver.

12 — Omni-bearing selector and course deviation indicator and radio magnetic indicator (RMI).

13 — AN/ARN–21 of Federal Telephone and Radio, airborne unit, military version with indicators ID 307 and ID 310.

14 — Omni-bearing selector ID 249 and radio magnetic indicator ID 250.

15 — Information without VOR airborne equipment for DMET supplement FTR 3544 with indicator unit ID 388.

16 — Total system including frequency standard (approx. 13.5 kg) instruments and cables, according to " Navarho Navigation ", published by the Federal Telecommunication Laboratories, June 1957.

17 — Mark 8 receiver and Flight Log are typical and is the model most widely used at present. All prices are to be understood FOB UK.

18 — Mark 8 receiver; average equipment. For details see Chapter 2.08, Table 1.

19 — Power pack, Model 277.

20 — Second set of decometers.

21 — Included in rent, see (25).

22 — Under development.

23 — Track plotter; not normally sold; usually let including maintenance. Price per year 2470 DM.

24 — Second Flight Log connected in parallel.

25 — Mark 5 receiver. Decometer indication, cables; not normally sold; usually let including maintenance. Price per year 4.640 DM.

26 — Rotary converter.

27 — Additional Decca Air Navigator system. For details see Chapter 2.09, Table 1.

28 — LORAN receiver EDO.

29 — LORAN equipment of RCA (Model LR-8803); MacKay (Model 4201A), EDO (Model 262A).

30 — Double receiver incl. power supply.

31 — Marine radio compass " Lodestar " Marconi, Model 2464A.

32 — Estimated.

33 — Total equipment according to " Navarho Navigation " published by the Federal Telecommunication Laboratories, June 1957.

34 — Estimated price for Test equipments.

35 — Mark 7B receiver, Model 876, intended for both Decca and DECTRA.

36 — Airborne equipment of the ITT Corp.

5. ABBREVIATIONS

A_0, A_1, A_2	Types of transmission.
A_0	Amplitude modulated; Absence of any modulation.
A_1	Telegraphy without the use of modulating audio frequency.
A_2	Telegraphy by the keying of a modulating audio frequency or audio frequencies, or by the keying of the modulated emission (special case: an unkeyed modulated emission).
ADF	*A*utomatic *D*irection *F*inder.
AFO	Ausschuss für Funkortung, Düsseldorf.
AGARD	Advisory Group for Aeronautical Research and Development, NATO, rue de Varenne, Paris.
A-station	Master transmitter of (Standard) LORAN.

ATR	Air Transport Radio—measure of volume of airborne equipment:
	one ATR = volume 1510 in^3 (approx.);
	width (B) 10.125 in. = 257 mm;
	length (L) 19.5625 in. = 496 mm;
	height (H) 7.625 in. = 194 mm (max.).

BFS	Bundesanstalt für Flugsicherung (Federal Administration of Air Navigation Services), Frankfurt/Main.
B-station	Slave station of (Standard) LORAN.
CAA	*C*ivil *A*eronautics *A*dministration.
Common system	Common military and civil air traffic control system in the U.S.A.
Consol and Consolan	Omni-directional radio range operating in the l.f. band, cf. System Description 2.02.
dB	Decibel; a measure of power ratios.
dBm	Decibel, related to 1 milliwatt (mW).
Decca	Hyperbolic radio navigation system operating in the l.f. band. See System Description 2.08.
DECTRA	*Dec*ca *T*racking and *Ra*nging: Hyperbolic radio navigation system, similar to Decca. See System Description 2.09.
DELRAC	*De*cca *L*ong *R*ange *A*rea *C*overage. Hyperbolic radio navigation system operating in the v.l.f. band, similar to Decca. See System Description 2.13.
DIAN	*D*ecca *I*ntegrated *A*irborne *N*avigation System (combined Decca Navigator, Dectra and Doppler system), See System Description 2.09.
dm	Ten centimetres.

DME	*D*istance *M*easuring *E*quipment. See System Description 2.04.
DMET	*D*istance *M*easuring *E*quipment *T*ACAN, similar to DME, used, however, with TACAN. See System Description 2.05.
EDO	EDO Corporation. American manufacturers of Loran receivers.
Elektra	Directional radio beacon with many beams in a fixed pattern. See System Description Consol and Consolan 2.02.
EPI	*E*lectronic *P*osition *I*ndicator radio navigation system for fixing. The distances to two fixed stations are obtained by measuring the transit time of pulses transmitted by an airborne transmitter on 1850 kc/s and reflected from the ground stations. See p. 14.
ETA	*E*stimated *T*ime of *A*rrival.
ETZ	Elektrotechnische Zeitschrift, VDE–Verlag, *Electrotechnical Journal*, published by the VDE–Verlag.
EUM	European Mediterranean Region (ICAO).
FCB	*F*requency *C*ontrol *B*oard.
FOB	Free on board.
FOB UK	Free on board United Kingdom.
FTZ	Fernmeldetechnisches Zentralamt der Deutschen Bundepost, Darmstadt and Fernmeldetechnische Zeitschrift, today NTZ.
F2	Telegraphy by the keying of a modulating audio frequency or audio frequencies, or by the keying of the modulated emission (special case: an unkeyed emission modulated by audio frequency).
Gee	British hyperbolic radio navigation system, similar to LORAN, operating, however, in the v.h.f. band.
HF = r.f.	Radio frequency.
H-rate	Designated a certain pulse recurrence frequency with a corresponding fixed channel separation. (LORAN, see System Description 2.10).
Hi-Fix	High-frequency, high-accuracy fixing; literature, see p . 14.
ICAO	International Civil Aviation Organization.
ILS	*I*nstrument *L*anding *S*ystem V.h.f. system of radio navigation which provides an aircraft, during its approach and landing, with lateral and vertical guidance and marker-beacon indications at specified points.
ILS–TAC	TACAN combined with ILS. See System Description 2.05.
IMRAMN	*I*nternational *M*eeting on *R*adio *A*ids to *M*arine *N*avigation (May 1946 in London).
ITT	*I*nternational *T*elephone and *T*elegraph Corporation, New York.

kHz = kc/s	Kilocycles per second.
km/s	Kilometres per second.
kVA	Kilovolt-ampere.
kW	Kilowatt.
lane	(Of the Decca system) : strip between two hyperbolae between which there exists a 360° phase shift.
Lear receiver	Airborne receiver manufactured by Lear Inc., Santa Monica, California.
L-rate	Designates a certain pulse recurrence frequency with a corresponding fixed channel separation Standard-LORAN. See System Description 2.10.
LORAC	*Lo*ng *R*ange *Ac*curacy system. Hyperbolic radio navigation system. It is based upon the phase difference measurement of moving hyperbolic pattern, it operates in the m.f. band. The system is known in France by the name RANA. See p. 14.
LORAN (Standard)	*Lo*ng *Ra*nge *N*avigation. American long-range hyperbolic radio navigation system operating in the m.f. band. See System Description 2.10.
LORAN–C	Developed from LORAN. See System Description 2.11.
LW = l.f.	Low frequency.
MHz = Mc/s	Megacycles per second.
Mio	Million.
μV	Microvolt.
μV/m	Microvolt per metre.
μsec	Microsecond.
msec	Millisecond.
MWh	Megawatt per hour.
mW	Milliwatt = 1/1000 watt.
mw	Magnetic north.
mw North–VOR	Magnetic north, related to VOR indication.
Navaglobe	V.l.f. long-range Rho–Theta radio navigation system. Supplies bearings only. See System Description 2.03.
Navarho	V.l.f. long-range Rho–Theta radio navigation system. Supplies bearings and distances. See System Description 2.07.
Navarho–H	See System Description 2.14.
Navarho–HH	See System Description 2.15.
Navarho–Rho	See System Description 2.16.
NARCO	National Aeronautical Corporation.
NF	Audio frequency.
NTG	Nachrichtentechnische Gesellschaft, Frankfurt/Main.
n.m.	Nautical mile.
Offset course	A course which does not lead away from or toward the ground station of a radio navigation system.
Omega	Hyperbolic radio navigation system. See System Description 2.13.

Omnitrac	Computer for the Decca system. See System Description 2.08.4.
P	Type of transmission: pulse modulation.
P_0	Absence of any modulation intended to carry information.
P2D	Telegraphy by the keying of a modulating audio frequency or audio frequencies, or by the keying of the modulated pulse (special case: an unkeyed modulated pulse).
P2F	Audio frequency or audio frequencies modulating the phase (or position) of the pulse.
Radio-Mailles	Hyperbolic radio navigation system. See System Description 2.12.
Radio-Mesh	English name of Radio-Mailles.
Radio-Web	English name of Radio-Mailles.
RANA	Hyperbolic *Ra*dio *Na*vigation system. See LORAC, pp. 14 and 193.
Raydist	American phase comparison system. See p. 14.
Rebecca–Eureka	Distance measuring and homing system: Rebecca: airborne equipment; Eureka: ground installation.
Rho–Theta System	Systems for position fixing by means of a bearing (Theta) and a distance (Rho) (e.g. VOR + DME, TACAN, Navarho).
RMI	Radio Magnetic Indicator.
r.m.s.	*R*oot *m*ean *s*quare.
RNG	Radio range = l.f. four-course range.
RTCA	*R*adio *T*echnical *C*ommittee for *A*eronautics.
RTCM	*R*adio *T*echnical *C*ommission for *M*arine Service.
s	Second
SEG Nachrichten	Technical journal of Standard Elektrik Lorenz AG. (SEL).
Shoran	*Sho*rt-*Ra*nge *N*avigation.
sm = n.m.	Nautical mile.
S-rate	Designates a certain pulse recurrence frequency with a certain channel separation (Standard-LORAN, see System Description 2.10.2).
SS–LORAN	*S*ky Wave *S*ynchronized *Loran*. LORAN System for very long distances. See System Description 2.10.
TACAN	*Tac*tical *A*ir *N*avigation. Short-range radio navigation system of the Rho–Theta type operating in the 1000 Mc/s band. See System Description 2.05.
TACAN Data Link	A system of TACAN data transfer. See System Description 2.05.
TDM	Thousand D-Mark (Federal Republic of Germany).
Telegon II	Telefunken–Goniometer–Peiler II.
T/R	Transmitter/receiver.
TVOR	Terminal VOR. See System Description 2.04.

4.3. Comparison of the Investment Required for the Airborne Equipment of Radio Navigation Systems

		Direction Finding (2.01)								CONSOL (2.02)	Navaglobe (2.03)
		Air			Sea						
4.3.2 Airborne equipment											
4.3.2.1 Price of radio equipment in thousand DM—weight (kg)—bulk (l.)	TDM	(1) 18.2	(2) 18.7	(3) 19.2	(4) 1.9	(5) 3.7	(6) 6.5	(7) 6.6	(31) 10.2	normal m.f. receiver	(8)
4.3.2.1.1 RF unit with aerial and including indicator unit for radio coordinate	kg	15.85	12.0	12.5	14–17	22–33	25	40	31.8		11.25
	l.	15.6	12.0	6.0	22–25	43–66	43	80	80		14.2
4.3.2.1.2 Remote control unit	TDM	1.9	2.2	3.2	not applicable						in 4.3.2.1.1
	kg.l.	1.6 2.3	1.4 1.5	2	not applicable						in 4.3.2.1.1
4.3.2.1.3 Power pack for 4.3.2.1.1 and 4.3.2.1.2	TDM	0.76	—		in 4.3.2.1.1						in 4.3.2.1.1
	kg.l.	2.2	—		in 4.3.2.1.1						in 4.3.2.1.1
4.3.2.1.4 Slave display of the radio coordinate	TDM	2.7	2.78	2.7	not applicable					not applicable	
	kg.l.	1.0	0.9	0.65	not applicable					not applicable	
4.3.2.2 Interpreting and display units	TDM	not applicable			not applicable					not applicable	not applicable
4.3.2.2.1 Pictorial display	kg.l.	not applicable			not applicable					not applicable	not applicable
4.3.2.2.2 Computer for the indication of the geographical position including display	TDM	not applicable			not applicable					not applicable	not applicable
	kg.l.	not applicable			not applicable					not applicable	not applicable
4.3.2.2.3 Ground speed computer and indicator	TDM	not applicable			not applicable					not applicable	not applicable
	kg.l.	not applicable			not applicable					not applicable	not applicable
4.3.2.2.4 Additional equipment proving the autopilot steering signal	TDM	not normally			not applicable					not applicable	not applicable
	kg.l.	not normally			not applicable					not applicable	not applicable
4.3.2.2.5 Automatic position reporting data coder without transmitter	TDM	not applicable			not applicable					not applicable	not applicable
	kg.l.	not applicable			not applicable					not applicable	not applicable
4.3.2.3 Current operating cost in thousand DM[32]											
4.3.2.3.1 Annual cost of valves		0.15	0.15	0.15	(4) 0.025	(5) 0.03	(6) 0.04	(7) 0.11			
4.3.2.3.2 Annual maintenance cost		0.20	0.20	0.20	0.11	0.26	0.40	0.53			

			VOR (2.04)		TACAN (2.05)	VORTAC VOR/DMET (2.06)	Navarho (2.07)	Decca (2.08)	
								Air	Sea
4.3.2 Airborne equipment									
4.3.2.1 Price of radio equipment in thousand DM—weight (kg)—bulk (l.)	TDM	(9) 14.0	(10) 14.3	(11) 4.5	(13) 27	(15) 20[34]	(16) approx. 45	(17) 20.5[18]	(25) 22.5
4.3.2.1.1 RF unit with aerial and including indicator unit for radio coordinate	kg	17.0	17.0	8.0	33	15	45	19	45
	l.	13.0		6.5	39	11	70	s. Tab. 1 in 2.08	s. Tab. 1 in 2.08
4.3.2.1.2 Remote control unit	TDM	0.45	0.50	not applicable	in 4.3.2.1.1	in 4.3.2.1.1	8	0.24[18]	not applicable
	kg.l.	0.4 0.29	0.5 0.56	not applicable	0.7 1.0	0.9 0.7	in 4.3.2.1.1	0.5	not applicable
4.3.2.1.3 Power pack for 4.3.2.1.1 and 4.3.2.1.2	TDM	1.0	1.0	in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1	1.94[18]	0.7
	kg.l.	3.7	3.8	—	in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1	10.5[19]	42.0[26]
4.3.2.1.4 Slave display of the radio coordinate	TDM	5.7[12]	5.7[12]	not applicable	5[14]	10[32]	not normally	3.06[20]	2.94[20]
	kg.l.	2.3	2.3	not applicable	3.8 2.7	1.3 0.1	not normally	2	14.5
4.3.2.2 Interpreting and display units	TDM		not applicable					13.64	13
4.3.2.2.1 Pictorial display	kg.l.		not applicable					13.0	61
4.3.2.2.2 Computer for the indication of the geographical position including display	TDM		not applicable					not applicable	not applicable
	kg.l.		not applicable					not applicable	not applicable
4.3.2.2.3 Ground speed computer and indicator	TDM		not applicable					not applicable	not applicable
	kg.l.		not applicable					not applicable	not applicable
4.3.2.2.4 Additional equipment proving the autopilot steering signal	TDM	(9) 8.4	(10) 8.4	(11) not normally				[22]	not applicable
	kg.l.	7.5	7.5	not normally				[22]	not applicable
4.3.2.2.5 Automatic position reporting data coder without transmitter	TDM			not applicable				[22]	not applicable
	kg.l.			not applicable				[22]	not applicable
4.3.2.3 Current operating cost in thousand DM[32]									
4.3.2.3.1 Annual cost of valves		0.2	0.2	0.2				1.0[21]	0.03[21],[23]
4.3.2.3.2 Annual maintenance cost		2.5	2.5	2.5				2.5[21]	2.25[21],[23]

		DECTRA (2.09)	STANDARD-LORAN (2.10)		LORAN-C (2.11)		Radio–Mesh (Radio/Web–Radio–Mailles) (2.12)	DELRAC and Omega (2.13)	Navarho–H (2.14)	Navarho–HH (2.15)	Navarho–Rho (2.16)
			Air	Sea							
4.3.2 Airborne equipment											
4.3.2.1 Price of radio equipment in thousand DM—weight (kg)—bulk (l.)	TDM	15.1[35]	(28) 18.2	(29) 11	(30) 85–130	(36)			(33)	(33)	(33)
4.3.2.1.1 RF unit with aerial and including indicator unit for radio coordinate	kg	26.8[35]	13	57–73	∼ 100	34			27	22.5	31.5
	l.		23.5	57–43	140	50			28	28	42.5
4.3.2.1.2 Remote control unit	TDM	0.65[27]	1.6	not applicable	not applicable				in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1
	kg.l.	1.0[27]	0.9	not applicable	not applicable				in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1
4.3.2.1.3 Power pack for 4.3.2.1.1 and 4.3.2.1.2	TDM	1.94[27]	in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1				in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1
	kg.l.	10.5[27]	in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1				in 4.3.2.1.1	in 4.3.2.1.1	in 4.3.2.1.1
4.3.2.1.4 Slave display of the radio coordinate	TDM	3.76[24]	not applicable	not applicable							
	kg.l.	4.5[24]	not applicable	not applicable							
4.3.2.2 Interpreting and display units	TDM	included in Decca Air Nav. Syst.	not applicable	not applicable							
4.3.2.2.1 Pictorial display	kg.l.	included in Decca Air Nav. Syst.	not applicable	not applicable							
4.3.2.2.2 Computer for the indication of the geographical position including display	TDM	not applicable	not applicable	not applicable							
	kg.l.	not applicable	not applicable	not appilcable							
4.3.2.2.3 Ground speed computer and indicator	TDM	not applicable	not applicable	not applicable							
	kg.l.	not applicable	not applicable	not applicable							
4.3.2.2.4 Additional equipment proving the autopilot steering signal	TDM	not applicable	not applicable	not applicable							
	kg.l.	not applicable	not applicable	not applicable							
4.3.2.2.5 Automatic position reporting data coder without transmitter	TDM		not applicable	not applicable							
	kg.l.		not applicable	not applicable							
4.3.2.3 Current operating cost in thousand DM[32]											
4.3.2.3.1 Annual cost of valves		0.9		0.18–0.31							
4.3.2.3.2 Annual maintenance cost		1.3		0.65–0.9							

UKW = v.h.f.	Very high frequency.
U/s = r.p.s.	Revolutions per second.
VA	Voltampere.
Vector-ratio-meter	Indicating instrument for taking the bearings in the Navaglobe/Navarho systems.
v.h.f.	Very high frequency.
VO Funk	Vollzugsordnung für den Funkdienst. See 2.10, pp. 113 [9] and 118.
VOR	V.h.f. omni-directional radio range. Short-range radio navigation system operating in the v.h.f. band. See System Description 2.04.
VOR/DMET	Combinations of VOR and TACAN techniques.
VORTAC	See System Description 2.06.
W	Watt.